Open University Geological Society Journal
Symposium Edition 2005
The Gathering
Stirling University 1-3 July 2005
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ISSN 0143-9472

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Editor: Jane Clarke

email: journal@ougs.org

OUGS Journal 26(2)
Symposium Edition 2005

Cover illustration: Thin sections of several different habits of barite. Photographs: Jane Clarke.

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Terrane spotting in the Himalaya

Professor Nigel Harris, Department of Earth Sciences, Open University, Milton Keynes

Abstract

The Tibetan plateau is the hinterland of the Himalayan orogen, comprising a collage of terranes. Since Carboniferous times these terranes have fragmented from the supercontinent of Gondwana and have drifted north before accreting onto the southern margin of Eurasia. The India-Asia collision which formed the Himalaya is the most recent example of this process and the resulting suture zone provides many of the characteristics that allow older terrane boundaries to be identified. Following the initial impact during the Eocene the northern margin of the Indian plate was disrupted by thrust zones, some of which have been proposed as ancient terrane boundaries. However, the recognition of terrane boundaries within monotonous and highly deformed metasediments, using field criteria alone, is problematical. Geochemical evidence from clastic sediments, including Nd-isotopes of bulk-rocks and U–Pb isotopes of detrital zircons, is helping to unravel the significance of disputed ancient terrane boundaries.

Introduction

The Earth's orogenic belts range in age from the Archaean to the present day but despite their wide age range they share many characteristics. Indeed, the Himalayan orogen provides a contemporary analogue for the processes that formed the Scottish Caledonides, even though the Caledonides were formed hundreds of millions of years ago during the Early Palaeozoic. For example, both belts are characterised by thrust tectonics in the outer zone, ductile deformation, high-grade metamorphism and decompression melting in the inner zone, and massive conglomerate deposits in the foreland basin. Furthermore, both result from convergence and collisions between discrete fragments of continental lithosphere that are termed terranes.

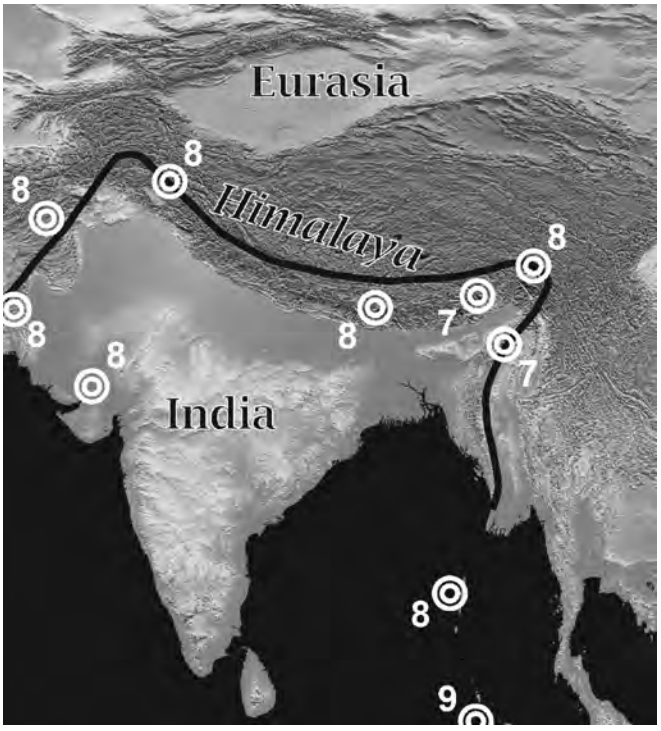

Figure 1. Digital elevation model of India, the Himalaya and Tibet. The suture bounding the Indian plate is marked as a heavy line. The circles indicate the epicentres of the largest earthquakes (with approximate magnitudes on the Richter scale) over the past 100 years. The 2004 tsunami was caused by the only magnitude 9 event recorded from the region.

One of the goals of orogenic studies is to define the boundaries of these terranes because only then is it possible to unravel the geometry of the collisions and the architecture of the orogen. This is a first step towards teasing out the fundamental processes that shaped the Earth's continental lithosphere.

The Indian-Asian Collision

Collision is not an event, it is a process. Since the tsunami of Boxing Day 2004, the inhabitants of the coastal regions of the Indian Ocean are well aware that they lie on a particularly active plate boundary. You can trace the plate boundary that caused this tragic event north-west from the subduction zone of the Indonesian arc through the strike-slip system of Burma into the convergent zone of the Himalaya that separates India from the rest of Asia (Figure 1). Most text books will state that collision between India and Asia occurred 50 million years ago so you would be forgiven for thinking that the suture represents a preserved Eocene collision zone. Although the initial collision did occur at around this time, continued convergence has resulted in persistent movement along this boundary. So when we are investigating ancient mountain belts it is important to avoid assigning specific ages to what may be long-lived processes.

Recognising the plate boundary between India and Asia has not proved difficult. Apart from active seismicity (Figure 1), there is evidence of contrasting polar-wandering paths from the two continental blocks and contrasting fossils from sediments deposited on opposite sides of the suture. Along the suture itself are fragments of ancient ocean floor, called ophiolites, that have been squeezed up between two converging continents. This suture can be traced along the Tsangpo valley through southern Tibet. It defines the southern boundary of the Trans-Himalayan batholith that is the consequence of the northwards subduction of an ancient ocean floor beneath the southern edge of Eurasia. Older suture zones have been recognised across the Tibetan plateau, using polar-wandering paths or Gondwanan faunal associations. The emerging picture is of successive fragments of Gondwana peeling off and migrating northwards since the Carboniferous or even earlier.

South of the Indo-Asian suture is Indian crust. Correlations can be made between pre-Cretaceous structures of India and those of the continents of Africa and Antarctica with which it was contiguous before the fragmentation of the Gondwanan supercontinent. The Himalaya marks the northern margin of the Indian plate where it has been deformed by a succession of thrust zones, similar in many respects to that of the Moine thrust zone in NW Scotland. One of the aims of Himalayan geologists is to define the extent of movement on each of the Himalayan thrusts and to assess its significance.

The Main Central thrust

Foremost amongst the north-dipping Himalayan faults is the Main Central thrust (Figure 2). The MCT is thought to have been

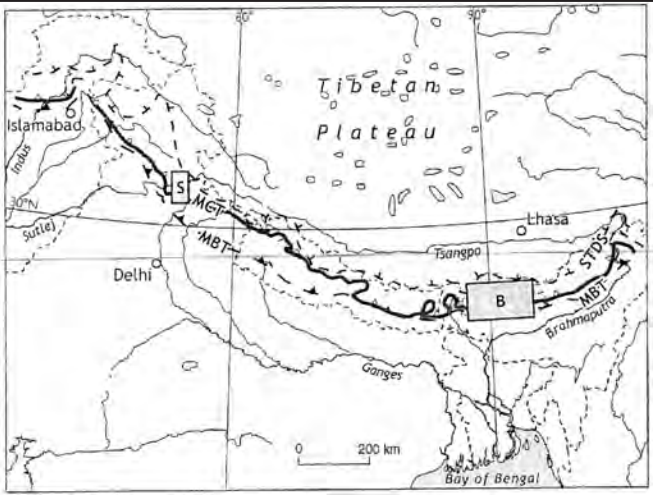

Figure 2. Map of the Himalaya showing the main tectonic breaks. MCT = Main Central thrust (heavy solid line), MBT = Main Boundary thrust (dashed), STDS = South Tibetan Detachment system (dashed). S = location of Sutlej sampling. B = location of Bhutan sampling.

active from the early Miocene, and today marks a change in topography between the high Himalaya and the lesser Himalayan foothills and continuing movement is marked by minor, shallow earthquakes. It also remains the site of numerous hot springs. You could map out the approximate location of the MCT by joining together all the villages in northern India and Nepal named Tatopani (meaning 'hot water' in Hindi). However, on the ground the precise location of this fault is much harder to pin down, partly because the rocks in both the hanging and the footwall are deformed and metamorphosed Proterozoic sedimentary sequences, containing few useful fossils for stratigraphic correlations.

The hanging wall of the MCT, to the north, comprises medium-high grade metasediments of Neo- to Mesoproterozoic age. To the south, in the footwall, are medium-low grade metasediments of Palaeoproterozoic age; the former are known as the High Himalayan Crystalline series (HHCS) and the latter as the Lesser Himalayan series (LHS). Both series comprise intercalations of quartzites, pelites and carbonates. In the field, it is not easy to recognise the tectonic break between them, largely because the fault is exposed at mid-crustal levels so that deformation is distributed across a high-strain zone of ductile deformation which is several kilometres thick (Figure 3). Different geologists have attempted to distinguish the HHCS from the LHS on the basis of deformation, or metamorphism or lithology, but no attempt has been universally accepted. Moreover, the significance of the MCT is strongly disputed. Some workers have suggested it represents several hundred kilometres of movement along a terrane boundary, others have suggested it represents a tectonic break within a single continental margin. In recent years, geochemical studies have proved useful in addressing these uncertainties.

Figure 3. The north-dipping fabrics of the MCT seen in the Langtang Himalaya, Nepal (view looking west).

Isotopes and clastic sediments

This contribution presents two techniques for characterising clastic sedimentary formations on the basis of the source regions from which they were derived. The first is the neodymium (Nd) isotope ratio measured from the bulk rock. Nd is a rare-earth element present in small amounts in virtually all rocks. One of its isotopes (^{143}Nd) is the daughter product of the decay of a samarium isotope (^{147}Sm). This decay system is useful firstly because the half-life of several billion years is appropriate for measuring geological timescales, and secondly because the rate of change of the isotope ratio ^{143}Nd/^{144}Nd is proportional to the Sm/Nd ratio of the rock, a ratio which decreases in a predictable way when the mantle melts to form basaltic magma. Once fixed in the melt, the Sm/Nd ratio remains unchanged by subsequent crustal processes, whether the melts experience fractionation or the crystallised rock is eroded, metamorphosed or even remelted. This means that the Nd-isotope ratio can be calculated as a model age, which is the estimated time since the Nd was initially extracted from the mantle. It is called a model age, because it is dependent on a geochemical model for the evolution of the mantle.

For a clastic sediment, the bulk rock may be derived from more than one source, and each source may incorporate Nd that has undergone many cycles of crustal reworking, so the model Nd age will represent the weighted average of all the crust-formation ages of the contributing sources. Sediments eroded from different terranes are likely to be derived from source regions of different ages and this contrast will therefore be reflected in their differing model Nd ages.

The western Himalaya

The first Nd-isotope study from the Himalaya was undertaken across the MCT in the Langtang valley, central Nepal. Since then, several studies have been undertaken in the central and western Himalaya, the most recent being in the Sutlej valley of NW India (Figure 2). The Sutlej is one of the major rivers flowing south from Tibet (Figure 4) onto the foreland basin of India, and its valley exposes a complete section through the HHCS and the LHS. When the isotope data from all these studies are combined, a remarkable picture emerges (Figure 5a). The model Nd ages for metasediments from the HHCS range from 1400 to 2200Ma, distinctly younger than those from the LHS (2200–2800Ma). This suggests that sedimentary packages from each lithological series have been derived from rocks of quite distinct ages and so has been cited as evidence that the MCT had brought together two distinct terranes.

However, a second geochemical approach has now been applied to Himalayan metasediments. Detrital zircons are found within every sedimentary formation of the HHCS and LHS. Zircons are possible to date because they incorporate small amounts of urani-

Figure 4. View of the High Himalaya of the Sutlej Valley (looking north) following the flash flood of 2000 that destroyed the infrastructure of the valley.

um which decay to lead; the relevant U-Pb decay schemes are the best studied of all radioactive decays used by geochemists. The date the zircon yields is the age since it crystallised from a melt because U-Pb isotopes are usually unchanged by cycles of erosion and deposition that the grain may have experienced following its magmatic history.

The zircon ages from the Himalayan metasediments are plotted in Figure 5b. For the LHS, zircon ages range from 1600 to 2800Ma, peaking in the interval 1600–1900Ma. The HHCS includes younger zircons, as young as 600Ma, with ages peaking at 1000Ma. However there are also zircons from the HHCS which cover the same, older, age span as the LHS zircons, and these also peak around 1700Ma.

By dating individual minerals it has therefore proved possible to resolve the ages of individual sources and so improve on the average ages obtained from the bulk-rock Nd data. We can now see

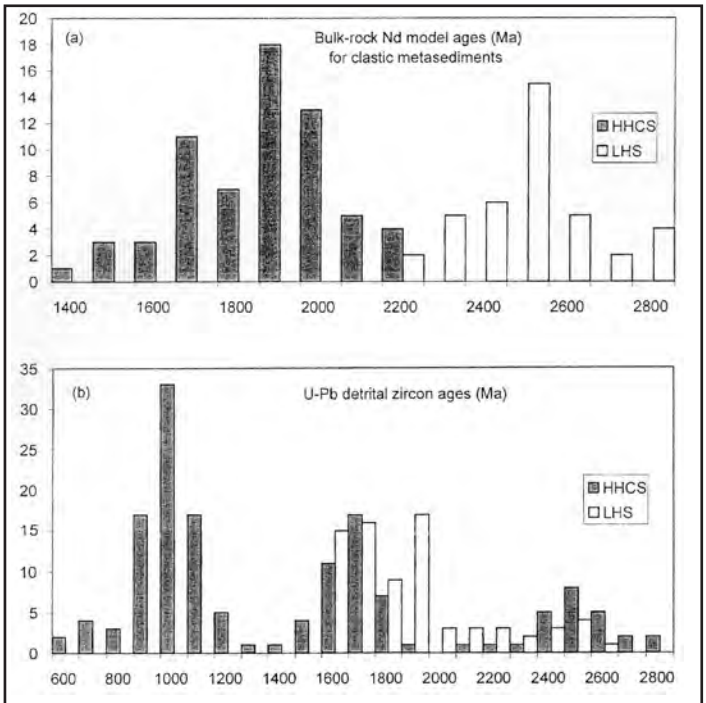

Figure 5. Geochemical data from the Sutlej valley, combined with data from Nepal (western and central Himalaya).

that HHCS zircons are derived from two sources; one, the younger group, is unique to the HHCS, but the older group is very similar to the LHS ages. So, instead of two quite different sources being involved, we now know that both the HHCS and the LHS shared a similar source; the younger bulk-rock Nd model ages from the HHCS result from a juvenile source also being involved in their formation. More detailed isotopic studies of the zircons using hafnium isotopes have confirmed that the HHCS and the LHS actually shared the same source. The fact that metasediments in both the hanging wall and the footwall of the MCT appear to have shared a common source argues against the thrust representing an ancient terrane boundary. The view gaining support is that although the MCT is a major thrust, it cuts through a single continental margin.

The eastern Himalaya

The eastern Himalaya are much less studied than the western regions. This is because of difficulties of access in Bhutan and NE India. However the first isotope study of clastic sediments from Bhutan (Figure 2) has just been completed, the final samples being collected during the OUGS field trip to western Bhutan in 2004 (Figure 6); the results are plotted in Figure 7.

Figure 6. View of the Taktstang monastery (Bhutan) built on the sillimanite gneisses of the High Himalaya.

For both techniques, there are fewer data than for the western Himalaya, but some trends are clear. As for the Sutlej region, the Nd model ages are much older for the LHS than for the HHCS, so the MCT marks a sharp break in source regions in the east as well as in the west of the orogen. The main distinction between the two datasets seems to be that there are no model ages less than 1700Ma from Bhutan whereas they extend as young as 1400Ma from the western Himalaya. There is also a lack of young ages for the zircon ages (none less than 1000Ma has been measured, compared with minimum ages of 600Ma from the Sutlej valley). This is probably due to deeper levels of erosion in the HHCS of the eastern Himalaya, exposing older stratigraphic levels, due perhaps to the eastwards increase in the intensity of the monsoon along the strike of the orogen. However the important observation

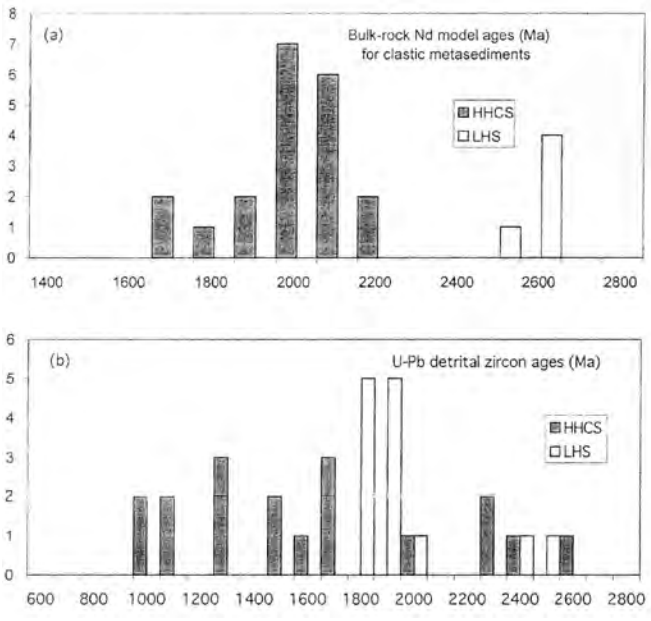

Figure 7. Geochemical data from Bhutan (eastern Himalaya).

for the present study is that the zircon ages from Bhutan divide into a younger component and an older component, the latter coinciding with the zircon ages from the LHS. In this respect the rocks are behaving in exactly the same way as in the Sutlej region, far to the west.

Discussion

Perhaps the most astonishing aspect of this geochemical study is that the principal lithological series of the Himalaya that were first mapped out in the field by Augusto Gansser in the 1930s, can be traced along strike by modern geochemical techniques for over 1000 km. In this respect the architecture of the Himalaya is quite simple. As a consequence, the MCT can be recognised using Nd bulk-rock analyses as a distinct break between two rock units derived from apparently different source regions. However the detrital zircon story adds some important detail to this simple picture. The two lithological series actually share a common source, but the formations of the HHCS are partially derived from an additional juvenile source area, which yielded zircons as recent as the youngest Precambrian, coincident with a period of granite magmatism in the north Indian craton. A collision zone may involve more than two terranes. Pacific- or Californian-type margins provide considerable scope for strike-slip terrane movement often involving short-lived island arcs. There are several possible candidates for this juvenile source from exposed rocks in northern India. Although we can not be sure of the overall movement that has been taken up by the MCT, the balance of evidence argues against it being an ancient terrane boundary.

There is one more aspect of this work that may prove to be equally significant for its geological implications. Most of the eroding detritus from the Himalaya have been transported by the Ganges and the Brahamputra rivers into the Bay of Bengal, the world's largest submarine fan (Figure 2). Drill core from the Bay of Bengal has been recovered and the cores studied to unravel the changing conditions during the exhumation of the orogen. More than half of this material has been transported by the Brahamputra system, but irrespective of where along the mountain belt erosion has taken place, our work suggests that the detritus will bear the isotopic fingerprint of the HHCS or the LHS, depending on which rocks are exposed at the time. Nd-isotope profiles from the cores show a sharp rise in Nd model ages during the late Miocene. This can now be interpreted as indicating the time at which the LHS was first exposed, important information for reconstructing the tectonic history of the orogen.

Book review

King of Siluria: How Roderick Murchison changed the face of Geology by John L Morton, 2004, Brocken Spectre Publishing, 276 pages, £12.99 (paperback) ISBN 0954682904.

Roderick Impey Murchison was born in 1792. After school he spent eight years as a soldier, during which time he served in the Peninsular War. He married Charlotte Hugonin in 1815 and for a time considered entering the church. However, in 1816 he and Charlotte embarked on a long continental tour and during their time in Paris he met Georges Cuvier for the first time. They spent time in Italy and were there when Vesuvius erupted in 1817.

On their return to England in 1818 they settled in Co Durham where Murchison enjoyed the life of a country gentleman, spending a great deal of time fox-hunting. In 1822 (they moved to Melton Mowbray where he pursued his hunting interests but by 1823 he was becoming rather bored and it was at this time that he met Sir Humphrey Davy who was the current President of the Royal Society. Murchison wrote that he "experienced much gratification in his lovely illustrations of great physical truths."

In late 1824 they moved to London and it was then that he took up a keen interest in science. He attended his first Geological Society meeting in January 1825 and formed friendships with Charles Lyell, Adam Sedgwick and William Buckland. He replaced Lyell as Honorary Secretary of the Geological Society in 1826 and in the same year he was elected a Fellow of the Royal Society - not for his scientific work but as "a man of means and leisure . . ."

As a man of private means he was able to travel all over Britain and Europe on geological excursions. His work with Sedgwick led to the naming of the Silurian and Devonian systems and it was on his first excursion to Russia that he named the Permian. Everywhere he went he met leading scientists and was entertained by royalty, including Czar Nicholas who honoured him for his work.

Murchison and Sedgwick became estranged over a disagreement of the base of the Silurian and at the end of the chapter entitled "Siluria" Morton includes an interesting Stratigraphical Correlation Table comparing Murchison's classification with our modem classification

In spite of his great pioneering work Murchison was somewhat arrogant and refused to accept the theory of Uniformitarianism or Darwin's theory of Evolution.

John Morton's book includes forty illustrations, sixteen in colour and there are four appendices: "The Primary Publications of Sir Roderick Murchison", "Geographical Features named after Sir Roderick Murchison", "The Geological Periods" and "The Will of Sir Roderick Impey Murchison". The author quotes extensively from Murchison's journals and letters and also from Archibald Geikie's Life of Sir Roderick I Murchison, written a few years after Murchison's death.

King of Siluria gives a fascinating insight into the way nineteenth century geological investigations were carried out by men of means who had the time and money to travel. If you are interested in the history of geology you will enjoy reading this book, which is very modestly priced.

Elizabeth Maddocks BA (Open)

New light on the Neoproterozoic evolution of the Moine supergroup - an exotic terrane within the Scottish Caledonides?

Dr Rob Strachan, School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Rd, Portsmouth, PO1 3QL

The research discussed in this talk is not mine alone but has been carried out in collaboration with various international geologists – a measure of the considerable interest worldwide in the classic Caledonian geology of Scotland. Today I would like to talk about the ways in which we might carry out terrane analysis in this ancient mountain belt, with specific reference to the enigmatic Moine rocks of the Northern Highlands of Scotland. We were introduced last night by Ian Dalziel to important concepts concerning terranes and the ways in which they might be identified within mountain belts. The terrane collage that makes up the west coast of North America in part resulted from the accretion of exotic terranes that collided obliquely with the ancient subduction zone that once existed along western North America and were then dispersed by strike-slip faulting along the continental margin. Precisely how to define a 'terrane' is a matter that has occupied many geologists. In the context of western North America, I think it is useful to distinguish between far-travelled 'exotic' terranes that have originated by accretion along a subduction zone and less far-travelled 'proximal' terranes that represent parts of the continental margin that have been sliced up and detached from their source by strike-slip faulting.

In Scotland, the Lower Palaeozoic Caledonian orogenic belt has, for the last 20 years or so, been divided up into a series of terranes, each separated from one another by major faults. The Hebridean Terrane is effectively the foreland to the orogen, and is limited to the east by the Moine Thrust. To the east lies the Northern Highland Terrane, dominated by complexly deformed and metamorphosed Precambrian metasedimentary rocks of the Moine Supergroup, the focus of this talk. The major Caledonian thrust and fold structures that occur between the Moine Thrust and the Great Glen Fault resulted from processes of continental collision during the convergence of three blocks, Laurentia, Baltica and Avalonia, and consequent closure of the Iapetus Ocean. In the context of ocean closure, it is therefore reasonable to ask whether or not the Moine rocks represent a truly 'exotic' terrane that was accreted to Laurentia during the Caledonian orogeny, or whether they might, more modestly, form a 'proximal' terrane that has always been associated with Laurentia.

The Moine rocks do not contain any fossils and it is therefore impossible to resolve the question of the affinities of these rocks on any palaeontological basis. The key lies in the application of modern geochronological techniques, in particular the high-precision U-Pb and Sm-Nd dating of minerals. Working from first principles, how do we establish the age of the Moine succession? Answer: it must be younger than the youngest detrital zircon that it contains, and older than the oldest igneous intrusion to cut it. What do we mean by detrital zircons? These are zircons that have been eroded from some igneous and/or metamorphic source terrain, to be deposited in a sedimentary basin. If we can date individual zircon grains, we know a) the age of the source rocks, and b) that the sediments that enclose these zircons can be no older than the youngest grain dated.

The Moine rocks commonly preserve sedimentary structures in areas of low tectonic strain. The precursor sediments were most likely deposited in shallow marine and/or fluvial settings. Detrital zircons from these sorts of metasediments have been dated and the results presented in histogram form by Peter Cawood for various samples collected from the Moine outcrop. The results indicate that the detrital zircons contained within the Moine rocks are mostly of Palaeo- and Mesoproterozoic age, with large peaks around 1500-1650Ma and 1100-1000Ma. The Moine rocks must therefore be younger than all of these. Importantly, some of these detrital grains are as young as 900Ma. In Inverness-shire, the Moine rocks are intruded by a series of highly deformed and metamorphosed granites, known as the West Highland Granite Gneiss. The dating of zircons from these granites, as well as a series of associated metagabbros near Invermoriston, gives an age of *c.* 870Ma. In summary, the Moine rocks must have been deposited after 900Ma (the age of the youngest detrital zircons) but before 870Ma (the age of the oldest intrusive igneous rocks).

As well as considering the Moine rocks, we must also not forget the extensive areas of basement gneisses that occur as inliers within the Northern Highland Terrane. These occur either in the cores of major folds, or as tectonic slices along major ductile thrusts such as the Sgurr Beag Thrust in Ross-shire. They are mostly banded, dioritic to granitic gneisses, formed as a result of the deformation and high-grade metamorphism of igneous rocks. These basement gneisses are thought to represent fragments of the basement on which the Moine sediments were deposited. In all cases, any traces of angular unconformity have been removed by high tectonic strain, but relict basal conglomerates sometimes occur within the Moine rocks adjacent to these inliers. Dating of zircons within four of these basement inliers, in Sutherland and at Glenelg, has yielded Archaean ages that are thought to date the igneous parent rocks (protoliths) of the gneisses.

In summary so far, we can therefore characterize the Northern Highland Terrane as comprising metasediments of the Moine Supergroup that were deposited at 900-870Ma on Archaean basement gneisses. How might these rocks correlate, if at all, with those that we see on the Caledonian Foreland east of the Moine Thrust Zone? Might they correlate, respectively, with the Torridonian sediments and the underlying basement gneisses of the Archaean-Palaeoproterozoic Lewisian Gneiss Complex? This tempting correlation has been proposed by many geologists since the early work of the Geological Survey. If we examine the detrital zircon histograms from two samples of the Torridonian we see that they are broadly similar to those obtained from the Moine, but in addition contain a significant number of Archaean grains which are generally absent from the Moine samples. This, as well as isotopic data that indicates that the Torridonian accumulated earlier than the Moines, at around 1000Ma, suggests that they may represent separate sedimentary successions. Recent investigations of the Lewisian Gneiss Complex indicate that it is itself made up of a series of different terranes. In most cases the

igneous protoliths are of Archaean age and were subject to a range of late Archaean to Palaeoproterozoic high-grade metamorphic events prior to amalgamation along late shear zones. The basement inliers east of the Moine Thrust Zone could correlate with parts of the Lewisian, but this is difficult to demonstrate one way or another.

Efforts to demonstrate lithotectonic linkages between the Foreland and the Northern Highland Terrane are thus inconclusive so far – we are apparently no farther forward in deciding whether or not the latter is 'exotic' or 'proximal' relative to the Foreland. One way of resolving this problem comes back to the study of detrital zircons. The peaks in the histograms must correspond to major tectonic events that occurred in the source terrain that was eroded to yield the Moine sediments. If we examine the likely disposition of major crustal blocks that were assembled at around 1000Ma to form the supercontinent Rodinia, where could the Moine sediments have originated? The source area for the Moine rocks must have contained rocks that formed at 1650-1500 and 1100-1000Ma. One obvious potential source is the basement of NE Canada. Detrital age peaks at 1650 and 1500Ma correspond closely to the Labradorian and Pinware magmatic events in that area; furthermore, the 1100-1000Ma detritus corresponds to the Grenville orogenic event. This source region is consistent with the overall N- or NE-directed palaeocurrents recorded within the Moine sediments (assuming no major rotation during deformation). The presence of 1650Ma detritus precludes input from Amazonia which lacks any recorded magmatic activity in the range 1700-1600Ma. A Baltica source is possible, but difficult to reconcile with the Moine palaeocurrent data. In summary, the available evidence is most consistent with deposition of the Moine sediments somewhere along the margin of Laurentia. They may well have been displaced laterally to bring them adjacent to the present Caledonian Foreland, but essentially all the indications are that the Moine rocks represent a 'proximal' terrane that has always been attached to Laurentia. There is no evidence that the Moine Thrust Zone obscures an oceanic suture.

I would now like to focus on the history of the Moine rocks during the Neoproterozoic. How and why did the Moine sedimentary basin form, and what happened to these rocks between their deposition and the Lower Palaeozoic orogeny? A generally accepted interpretation proposed by Ian Dalziel and Jack Soper is that the Moine sedimentary basin resulted from the abortive break-up of Rodinia as crustal blocks rifted off western Laurentia to form the palaeo-Pacific Ocean. The Moine was intruded during the Neoproterozoic by various granites, gabbros and pegmatites that have yielded isotopic ages in the region 870-740Ma. Much discussion has focused on the possible significance of these early igneous bodies that are now invariably strongly deformed and metamorphosed. The granitic intrusions and the pegmatites show evidence for having been derived from the melting of Moine rocks at deeper crustal levels and so geochemical parameters cannot be used to predict the tectonic environment with any certainty. Two contrasting models have therefore been proposed for the Neoproterozoic evolution of the Moine. The first envisages more or less constant crustal extension and sedimentation, with associated igneous intrusions forming as a result of crustal heating during rifting (these intrusions might be comparable to the Tertiary igneous complexes associated with the Red Sea, for example). The second interprets the granites and pegmatites to have resulted from high-grade metamorphism of the Moine rocks during a Neoproterozoic (Knoydartian) orogeny. How might we be able to distinguish between these two models? The answer lies in the isotopic dating of early metamorphic minerals that can be tied into pressure-temperature (PT) paths. The rifting model cited above would result in high temperature, low-pressure metamorphic assemblages, whereas the orogenic model would be associated with moderate to high pressure metamorphism.

In the western Moine of Morar, the Moine rocks show evidence for polyphase deformation. D1 isoclinal folding on a nappe scale interfolded the Moines with basement gneisses, and was followed by widespread growth of garnet. This was then followed by intense D2 folding and schistosity development. The garnets show spectacular zoning, with an inner core and outer rims forming during prograde metamorphism to a peak of 600-650ºC and 10-12kbar (= 30-35km burial). These sorts of PT conditions are only consistent with the orogenic model – not the rifting interpretation. Derek Vance carried out Sm-Nd dating of garnets from four separate localities and obtained ages in the region 820-790Ma. These are thought to closely correspond to the timing of peak metamorphism, thus substantiating the concept that a Neoproterozoic (Knoydartian) orogeny affected the Moine rocks.

This information has been published for some while now. New, unpublished data from Sutherland obtained by Martin Hand lends further support to the orogenic model. In west Sutherland, Moine metasediments include garnetiferous pelites, and both the Moine rocks and the basement inliers are intruded by meta-igneous bodies such as the Ben Hope Sill, now a garnet amphibolite. As in Morar, garnet growth occurred post-D1 and pre-D2, as a result of prograde increases in temperature and pressure. Recent Sm-Nd dating of garnets from two separate Moine pelites as well as the Ben Hope Sill has yielded similar ages of 820-790Ma, suggesting that the Knoydartian orogenic event recorded in Morar is widespread in the western Moine.

Further complexity to the tectonic history of the Moines is indicated by recently acquired, unpublished data from the Moines of the Druimnadrochit area. These are high-grade migmatites, studied by Martin Emery as part of his PhD project. The migmatites show a prograde PT path that culminates in melting at temperatures of 800ºC and pressure of 8-10kbar, again consistent with crustal thickening and orogeny. Zircon rims that grew during this melting event have been dated by Pete Kinny and Clark Friend at 727 ± 6Ma. This indicates an additional and distinctively younger orogenic event than that identified in the western Moine. Support for a *c.*730Ma orogenic event is provided by similar U-Pb titanite ages obtained from the Moine rocks around Lochailort by Geoff Tanner and Jane Evans.

The implication of the recently acquired data is that the Moine rocks were affected by not one, but TWO orogenic events during the Neoproterozoic, the first at 820-790Ma, and the second at 730Ma. It is worth pointing out that similar-aged high-grade metamorphic events have been recorded east of the Great Glen Fault within the Moine-like rocks that sit beneath the Dalradian in the northern Central Highlands. Various pegmatites that have yielded isotopic ages in the general time brackets of these orogenic events presumably formed by melting during crustal thickening. Nonetheless, it seems likely that the oldest granites and gabbros that were intruded at around 870Ma probably formed

during crustal extension and development of the Moine sedimentary basin. We are accustomed to interpreting orogenic events as the result of plate interactions at subduction zones. However, this sort of interpretation is difficult to sustain for Neoproterozoic orogeny in the Moine because most palaeocontinental reconstructions show the Moine rocks firmly in the middle of Rodinia, well away from any plate boundaries. There is no evidence within the Moine for any Neoproterozoic calc-alkaline igneous rocks or for ophiolites of this age – key indicators of plate margin orogenic activity. How can we have orogenic activity in such a setting?

A possible solution to this problem arises from a suggestion by Peter Cawood that we might gain insight into the Moines by examining the history of the Centralian Superbasin in Australia. This is a huge sequence of sediments that was affected by the Petermann orogeny at ~560Ma and the Alice Springs orogeny at ~350Ma. Both orogenic events were associated with 'thick-skinned' imbrication of basement and cover as well as high-grade metamorphism. The most important point to make is that there is very good evidence that at this time Australia was within the Rodinia supercontinent, some distance away from any contemporary plate margins. Orogenic activity apparently occurred within the craton, hence the term 'intracratonic orogeny'. Why did it occur? It is generally considered that crustal stretching and development of the Centralian Superbasin may have corresponded to periods of steep subduction along the Rodinian active margin, whereas periods of orogeny inboard of the subduction zone may have resulted either from flat-slab subduction or terrane collision. Just such a process of intracratonic orogeny could perhaps have been responsible for the Neoproterozoic orogenic events recorded within the Moines. Comparison of the areal extent of the Australian Superbasin with the outcrop of the Moines reminds us just how small the Scottish Highlands are.

In summary:

1) The Moines are likely to have been deposited along the Laurentian margin during the early Neoproterozoic. There is no evidence for an 'exotic' origin, and they most likely represent a 'proximal' terrane that was displaced along the Laurentian margin during the Caledonian orogeny.

2) The Moine rocks appear to have been affected by two prograde 'Knoydartian' orogenic events during the mid-Neoproterozoic; these may represent intra-cratonic orogenies. Over large tracts of the Moine, the only remnants of these events are the earliest isoclinal folds and porphyroblasts.

3) A western tectonic boundary to Knoydartian orogenic events presumably lies buried in the footwall to the Moine Thrust as there is no trace of these events on the Caledonian Foreland. The presence of Moine-like rocks carrying evidence for 840-800Ma metamorphism in the Central Highlands suggests linkage across the Great Glen Fault which also cannot therefore be a terrane boundary of any great significance.

Book reviews

The Solid Earth 2nd Edition by C.M.R. Fowler, 2004, Cambridge University Press, 685pp, £33.00 (paperback) ISBN 0521584094.

Having been familiar with the first edition of this book during my undergraduate and post-graduate degrees I was eager to see how the second edition had evolved.

This text book covers all of the classic areas of geophysics including plate tectonics, magnetics, gravity and seismology. It definitely has a mathematical slant. A preliminary glance at the contents shows very little change in the structure, a closer inspection shows that chapter eight on the Earth's core and deep interior has been split out from the heat chapter in the first edition. This makes sense as there has been intense research in this area since the publication of the original.

Most of the chapters have been brought up to date with new clear pictures and diagrams and fairly current references and bibliographies. The colour plates in the centre show a mouth-watering selection of models, charts and maps, the 3-D convection models of the mantle being my particular favourite.

This is an excellent text book and it is a must for anyone seriously wanting to study geophysics: it has been called the "Holmes of Geophysics" and I would agree. Even for those who just enjoy geophysics it is a great reference and the glossary is invaluable. If anyone has the original though I would borrow a copy and see if your area of interest is one of the significantly updated areas. Otherwise the first edition certainly stands the test of time.

Samantha Aderson, BSc(Hons) University of Liverpool, MPhil (Open)

The Geology of Scotland 4th Edition, by Nigel H.Trewin (Ed.), 2002, The Geological Society, London, 483pp, £27.50 (paperback) ISBN 1862391262.

A reference book with the ability to con you into thinking that you can just pick it up to have a quick read about your favourite area. It is a book-lovers dream with colour photographs, many, many excellent diagrams of cross-sections and maps and the text is host to facts galore!

The changed format to previous editions, now has 34 authors and 20 chapters all reflecting the diverse geology of Scotland both in time and rock types. A section on the terranes of Scotland, is preceded by first, an initial introduction to the geology and then the importance of 19th century Scottish geologists to their science.

Chapters on the post-Caledonian Geological History then follow. They feature the Old Red Sandstone and Carboniferous through to the Quaternary, including the Tertiary igneous activity, of course. The final chapters cover Economic and Environmental Geology with subjects such as, Metalliferous minerals, Coal, Hydrocarbons and Bulk Materials.

This book will be a constant source of information for any buyer and is certainly one that I would recommend. It is easy to read for the post-graduate and certainly one that any student of geology should have, or at least have access to, in a library. The book has attempted to tell the story of the geological evolution of Scotland. Priority being given to on-shore geology, in the hope that it will encourage us to go into the field and visit some of the world-class Scottish geology.

It has certainly whetted my appetite to see more of these sites and I have made an Old-year resolution to do just that. So look out Scotland here I come! My only problem is, which site shall I go to first and how can I choose between the Ballantrae Complex and Inchnadamph ..... or even Mull.

Yvonne Lewis-Cutt, BA Hons (Open)

Caledonian granite dating, Scottish accretion and the weather

Dr Grahame Oliver, Crustal Geodynamics Group, School of Geography and Geosciences, University of St Andrews

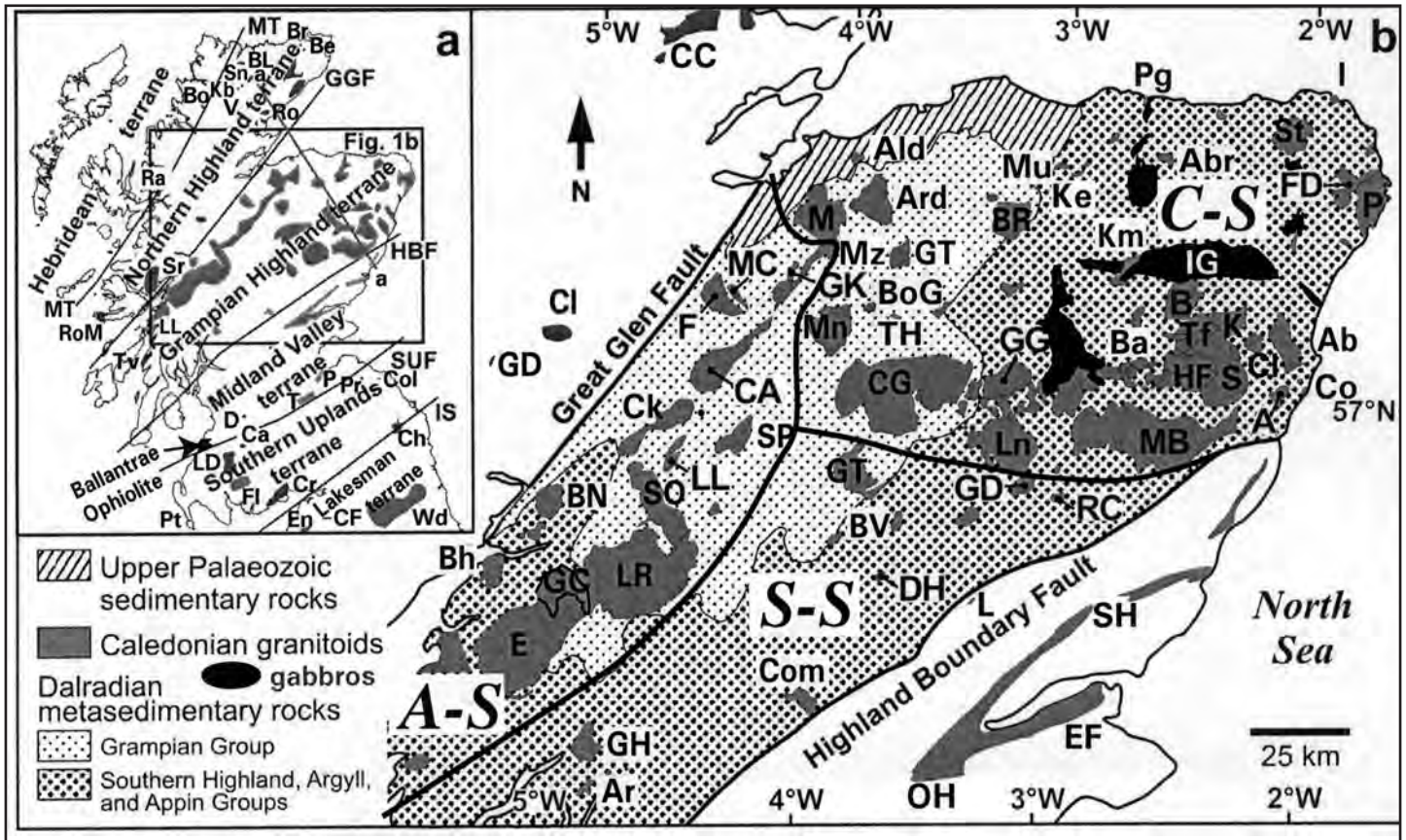

Figure 1. Maps drawn by G Steinhöefel and G Oliver showing a) Inset, Scottish terranes and distribution of granites: MT Moine Thrust, GGF Great Glen Fault, HBF Highland Boundary Fault, SUF Southern Upland Fault, IS Iapetus Suture. b) Main Figure, simplified geological map of the Grampian Highland terrane and magmatism. A-S Argyll Suite, C-S Cairngorm Suite, S-S South of Scotland Suite. Key to granite and other abbreviations given in Table 1. Modified after Stephenson & Gould (1995) and Trewin & Rawlin (2002).

Introduction

The aim of this contribution is to summarise the ages of Caledonian granites in Scotland, use this data to refine models of Scottish Caledonian plate accretion and to speculate on how these plates may have interacted with wind belts to affect climate and the weather. Figure 1 shows the division of Scotland and northern England into tectonostratigraphic terranes and the distribution of Late Proterozoic and Ordovician to Devonian granites, gabbros and lavas.

Geochronology of Scottish Caledonian granites

In the late Twentieth Century, the dating of Caledonian granite intrusions in Scotland relied on Rb-Sr, K-Ar and bulk zircon U-Pb radiometric dating methods. These methods have deficiencies (see discussion in Oliver 2002) and have been superseded by U-Pb single grain zircon geochronology, in particular using Cathode Luminescence, Sensitive High Resolution Ion Microprobe (SHRIMP) and Thermal Ionisation Spectrometry (TIMS) technology which avoids problems such as slow cooling, hydrothermal resetting or inheritance.

Table 1 lists reliable U-Pb zircon ages of the Scottish late Neoproterozoic and Caledonian igneous rocks plus less reliable Rb-Sr and K-Ar age dates from northern England. It includes unpublished SHRIMP zircon ages obtained by G. Oliver and S. Wilde at Curtin University of Technology, Perth, Australia, and by G Oliver, S Wilde and Y Wu at the Beijing Shrimp Centre, Chinese Academy of Geological Sciences, China. Also included is an unpublished TIMS zircon age of the Portsoy gabbro measured by M Martin and D Condon at the Department of Earth, Atmosphere and Planetary Sciences, Massachusetts Institute of Technology, USA. It is not proposed to discuss the details of the SHRIMP and TIMS dating in this publication. Suffice it to say that the new dates are based on means of $^{206}Pb/^{238}U$ ages of near concordant zircon magmatic overgrowths (SHRIMP) and abraded single grains (TIMS). Figure 2 is a probability density distribution diagram of these ages: there are 6 age spikes labeled as rifting, collision, start of subduction, roll-back and slab break-off as explained below. Figure 3 summarises the ages of Neoproterozoic and Caledonian magmatism north of the Highland Boundary Fault, groups the ages according to Figure 2, and notes activity in neighbouring terranes and comments on the regional tectonic environment.

Table 1. Summary of age dates from Scotland and Northern England

Given in the order: name, abbreviation in Figure 1, method, age and error (Ma), reference.

NW Highlands: Berridale granite, Be, U-Pb zircon, 599±9, Kinny *et al* 2003(b); Cairn Quinneag granite, CC, U-Pb zircon, 593.2±3.3, Oliver *et al.* un pub; Braeval granite, Br, U-Pb zircon, 588±8, Kinny *et al.* 2003(b); Glen Dessary syenite, GD, U-Pb zircon, 456± 5, van Breemen *et al.* 1979; Borrolan syenite, Bo, U-Pb zircon, 430±4, van Breemen *et al.* 1979; Strathnaver granite, Sn, U-Pb zircon, 429±11, Kinny *et al.* 2003(a); Clunes granite, Cl, U-Pb zircon, 428±2, Stewart *et al.* 2001; Ben Loyal granite, BL, U-Pb zircon, 426±9, Halliday *et al.* 1987; Strontian granodiorite, Sr, U-Pb zircon, 425±3, Rogers & Dunning 1991; Ratagain granite, Ra, U-Pb badellyite , 425±3, Rogers & Dunning 1991; Ross of Mull granite, RoM, U-Pb zircon, 420.7±4.7, Oliver *et al.* un pub; Klibreck granite, K, U-Pb zircon, 420±6, Kinny *et al.* 2003(a); Vagastie Bridge granite, V, U-Pb zircon, 424±8, Kinny *et al.* 2003(a); Strontian granite, Sr, U-Pb zircon, 418±1, Paterson *et al.* 1993.

Grampians: Muldeary granite, Mu, U-Pb zircon, 611±15, Oliver *et al.* un pub; Keith granite, Ke, U-Pb zircon, 601±4, Mendum *et al.* 2002; Portsoy granite, Pg, U-Pb zircon, 601±4, Mendum *et al.* 2003; Tayvallich lavas, Tv, U-Pb zircon, 601±4, Dempster *et al.* 2002; Ben Vuirich granite, BV, U-Pb zircon, 590±2, Rogers *et al.* 1989; Kemnay granite, Ke, U-Pb zircon, 475.6±9.6, Oliver *et al.* un pub; Tillyfourie granite, Tf, U-Pb zircon, 474±11, Oliver *et al.* un pub; Auchlee granite, A, U-Pb zircon, 473±13, Oliver *et al.* un pub; Rough Craig granite, RC, U-Pb zircon, 472.9±6.7, Oliver *et al.* un pub; Portsoy Gabbro, Pg, U-Pb zircon, 471.5±0.7, Martin & Condon. un pub; Cove granite, Co, U-Pb zircon, 471±21, Oliver *et al.* un pub; Aberdeen granite, Ab, U-Pb monazite, 470±1, Kneller & Aftalion 1987; Inch Gabbro, IG, U-Pb zircon, 470±9, Dempster *et al.* 2002; Strichen granite, S, U-Pb zircon, 467, 6, Oliver *et al.* 2000; Kennethmont granite, Km, U-Pb zircon, 457±1, Oliver *et al.* 2000; Inzie granite, I, U-Pb zircon, 455.1±7.4, Oliver *et al.* un pub; Kyllachy granite, Kg, U-Pb zircon, 453.6±6.5, Oliver *et al.* un pub; Moy granite, M, U-Pb zircon, 453.1±5.4, Oliver *et al.* un pub; Strath Spey granite, SP, U-Pb zircon, 449.1±7.2, Oliver *et al.* un pub; Aldearn granite, Ald, U-Pb zircon, 432±10, Oliver *et al.* un pub; Garabal Hill appinite, GH, U-Pb zircon, 429±2, Rogers & Dunning 1991; Strath Ossian granite, SO, U-Pb zircon, 428.2±4.5, Oliver *et al.* un pub; Ballachulish granite, Bh, U-Pb zircon, 427±1, Fraser *et al.* 2004; Ruhba Mor appinite, RM, U-Pb titanite, 427±3, Rogers & Dunning 1991; Aberchirder granite, Abr, U-Pb zircon, 426.8±5.8, Oliver *et al.* un pub; Arrocher appinite, AR, U-Pb titanite, 426±3, Rogers & Dunning 1991; Foyers granite, F, U-Pb zircon, 425.8±4.3, Oliver *et al.* un pub; Maol Chnoc granite, MC, U-Pb zircon, 420±4.3, Oliver *et al.* un pub; Clinterty granite, Cl, U-Pb zircon, 419±13, Oliver *et al.* un pub; Lochnagar granite, Ln, U-Pb monazite, 417±1, Parry *et al.*2003; Glen Doll Diorite, GD, U-Pb zircon, 416.5±4.9, Oliver *et al.* un pub; Glen Gairn granite, GG, U-Pb monazite, 415±1, Parry *et al.* 2003; Mazearn granite, Mz, U-Pb zircon, 413.1±9.7, Oliver *et al.* un pub; Etive granite, E, U-Pb zircon , 413±10, Oliver *et al.* un pub; Comrie diorite, Com G, U-Pb zircon, 411±16, Oliver *et al.* un pub; Monadhlith granite, M, U-Pb zircon, 410.9±5.7, Oliver *et al.* un pub; Boat of Garton granite, BoG, U-Pb zircon, 410.6±9.9, Oliver *et al.* un pub; Loch Rannoch granite, LR, U-Pb zircon, 410.2±5.9, Oliver *et al.* un pub; Tore Hill granite, TH, U-Pb zircon, 410±6.1, Oliver *et al.* un pub; Bennachie granite, B, U-Pb zircon, 409.8±5.3, Oliver *et al.* un pub; Glen Coe Ring Dyke, GC, U-Pb zircon, 408±13, Oliver *et al.* un pub; Cairngorm granite, CG, U-Pb zircon , 407±22, Oliver *et al.* un pub; Comrie granite, Com D, U-Pb zircon, 406.6±10.4, Oliver *et al.* un pub; Ballater granite, Ba, U-Pb zircon, 406.3±6.7, Oliver *et al.* un pub; Ardclach granite, Ard, U-Pb zircon, 406.5±5.6, Oliver *et al.* un pub; Glen Coe rhyolite, GC, U-Pb zircon, 406±6, Fraser *et al.* 2004; Ben Rinnes, BR, U-Pb zircon, 406±13, Oliver *et al.* un pub; Loch Laggan felsite, LL, U-Pb zircon, 406±14, Oliver *et al.* un pub; Mount Beattock granite, MB, U-Pb zircon, 405.7±4.8, Oliver *et al.* un pub; Skene granite, S, U-Pb zircon, 403±12, Oliver *et al.* un pub; Hill of Fare granite, HF, U-Pb zircon, 403±8.4, Oliver *et al.* un pub; Glen Coe andesite, GC, U-Pb zircon, 398±2, Fraser *et al.* 2004; Glen Tilt granite, GT, U-Pb zircon, 390.2±7.5, Oliver *et al.* un pub.

Midland Valley: Sidlaw Hills andesite, SH, Rb-Sr, 423.6±6.1, Thirlwall 1988; Ochil Hills andesite, OH, Rb-Sr, 416.1±6.1, Thirlwall 1988; Lintrathen ignimbrite, L, Rb-Sr, 415.5±5.8, Thirlwall 1988; Distinkhorn granodiorite, D, Rb-Sr, 412.8±5.5, Thirwall 1988; Pentland Hills rhyodacite, P, Rb-Sr, 412.6±5.7, Thirlwall 1988; Tinto Felsite, T, Sm-Nd, 411.9±1.9, Thirlwall 1988; Ochil Hills diorite, OH, Rb-Sr, 411.4±5.6, Thirlwall 1988; East Fife rhyolite, EF, Rb-Sr, 410.6±5.6, Thirlwall 1988;

Southern Uplands: Cockburnlaw granite, Col, Rb-Sr, 413.7±4.2, Thirlwall 1988; Cainsmore of Carsphairn, Ca, Rb-Sr, 410.4±4, Thirlwall 1988; Priestlaw granite, Pr, Rb-Sr, 408.5±5.6, Thirlwall 1988; Loch Doon granite, LD, K-Ar, 408±2, Stephens & Halliday 1979; Portencorkie granite, Pt, U-Pb zircon, 397.6±5.3, Oliver *et al.* un pub; Criffel granite, Cr, Rb-Sr, 397±2, Stephens & Halliday 1979; Cairnsmore of Fleet granite, Fl, Rb-Sr, 392±2, Stephens & Halliday 1979;

Northern England: Carrock Microgranite, CF, U-Pb zircon, 452.4±4.1, Millward & Evans 2003; Borrowdale Crinkle Tuff, BV, U-Pb zircon, 452.8±0.7, Millward & Evans 2003; Ennerdale granite, En, U-Pb zircon, 452±4, Millward & Evans 2003; Borrowdale Little Stand Tuff, BV, U-Pb zircon, 451.6±1.4, Millward & Evans 2003; Threlkeld granite, TG, U-Pb zircon, 451±1.1, Millward & Evans 2003; Eskdale granite, EG, U-Pb zircon, 450±3, Hughes *et al.* 1996; Stockdale rhyolite , SR, Rb-Sr, 430±7, Compston *et al.* 1982; Weardale granite, Wd, Rb-Sr, 410±10, Holland & Lambert 1970; Wensleydale granite, Wy, Rb-Sr, 400±10, Dunham and Wilson 1985; Skiddaw granite, Sk, K-Ar, 399±4, Shephard *et al.* 1976; Shap granite, Sh, K-Ar, 397±7, Wadge *et al.* 1978; Cheviot lava, Ch, Rb-Sr, 395.9±3.8, Thirlwall 1988; Cheviot granite, Ch, Rb-Sr, 395.9±2.9, Thirlwall 1988.

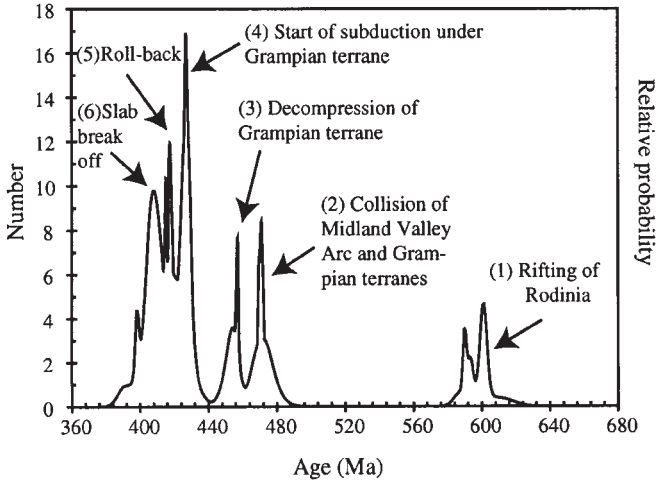

Figure 2. Probability density distribution diagram of late Neoproterozoic and Caledonian granite and gabbro $^{207}U/^{235}Pb$ ages from north of the Highland Boundary Fault with plate tectonic interpretations. Data from Table 1.

~ 600 Ma: Rift granites

The ~600 Ma granites have εNd -6, $\delta^{18}O$ 8-9 (Harmon *et al.* 1984) and $^{87}Sr/^{86}Sr$ initial ratios of 0.710-0.718 (Long 1964, Pankhurst & Pidgeon 1976). The Carn Chuinneag intrusion includes riebekite bearing granite typical of A-type (anorogenic) granites formed during continental rifting (Loiselle & Wones 1979). The contemporaneous Tayvallich basaltic lavas are also typical of rifted environments (Graham 1986). This bimodal magmatism is contemporaneous with bimodal magmatism in the Appalachians and the Norwegian Caledonides and has been assigned to the break up of the supercontinent Rodinia which led to the formation of the Iapetus Ocean (Soper 1994). Although these granites and basalts are arguably pre-Caledonian, they were metamorphosed and tectonised during either the ~470Ma Grampian or the ~430Ma Scandian episodes (see below).

~ 470Ma: Grampian episode collisional granites

There is a gap in granite activity between 585 and 485Ma, when the Iapetus Ocean was spreading and the Laurentian margin remained passive. Syn-regional metamorphic granites were intruded at ~470 Ma. These foliated granites are typically muscovite, biotite (and rarely tourmaline) bearing and have εNd -10 to -11, $\delta^{18}O$ 9-11 and $^{87}Sr/^{86}Sr$ initial ratios >0.712 (Harmon *et al.* 1984), typical of S-type granites formed by the melting of sedimentary protoliths (Chappell & White 1974). The Newer Gabbros have been dated at 470-471Ma (Table 1). Buchan and Barrovian regional metamorphism in the Grampian terrane have been dated at 470Ma (Oliver *et al*. 2000, Baxter & ague 2002). Obduction of the Ballantrae ophiolite has been dated at 478+/-8 Ma (K-Ar age of hornblende from the metamorphic sole, Bluck *et al.* 1980). Oliver (2001) related the collision and accretion of the Midland Valley arc terrane to the Laurentian margin (Grampian terrane) with this obduction. Therefore, there is a temporal link between collision, gabbro intrusion, regional metamorphism and crustal melting at 470Ma: this is the Grampian episode of the Caledonian Orogeny.

According to Thompson (1999) normal mantle heat flow and radioactive heating of a crust doubly thickened by collision would take at least 20Ma to heat up to its metamorphic peak. However, the Barrovian and Buchan metamorphism coincided with the collisional thickening at 470Ma, consequently heat must have been added to the crust during collision. One way to accomplish this is by intrusion of the 470Ma granites and gabbros. The latter have mantle-like $^{87}Sr/^{86}Sr$ initial ratios 0.7032 (Pankhurst 1969) and arc chemistry (Thompson 1985). Figure 4a illustrates how the Newer Gabbros may represent a plutonic arc that formed as the Highland Border back arc was subducted below the Grampian terrane. The subducted plate broke off along its spreading ridge thus promoting asthenospheric upwelling, partial melting, crustal underplating and enhanced crustal heat flow (Oliver 2002).

The results of geobarometry (Baker 1985) show that Grampian Barrovian metamorphism occurred at up to depths of 35km (1 GPa). Since the present day Grampian crust is of normal (35km) thickness (Hall *et al.* 1984) and 1 GPa metamorphics are at the present day surface, it can be assumed that the Barrovian crust was double normal thickness at 470Ma, i.e. ~70km. The mid-Llanvirn (465Ma) Kirkland Conglomerate lies unconformably over the Ballantrae ophiolite and contains mostly ophiolite and some granite debris but also Barrovian high grade garnet detritus which Hutchison & Oliver (1998) and Oliver (2001) considered to be evidence for deep erosion of the Grampian terrane only 5Ma after the peak of metamorphism. To get 35km deep metamorphosed crust to the surface in 5Ma, requires an erosion rate of 7.4mm/yr, similar to the erosion rate being experienced in the 8.1km high Nanga Parbat region of the present day Himalaya where 15-20 km has been unroofed in the past 3Ma (Zeitler *et al*. 2001).

~ 450 Ma: Grampian episode decompression granites

The 457+/-1 Ma Kennethmont granite is the oldest non-foliated granite in the Grampian terrane (Figure 3) and therefore dates the end of deformation and regional metamorphism. The ~450Ma granites have similar isotopic characteristics as the collisional granites: εNd = 10.0, $\delta^{18}O$ = 8.5-11, and $^{87}Sr/^{86}Sr$ initial ratios greater than 0.712 (Harmon *et al*. 1984), again typical of S-type granites. The Glen Dessary intrusion has a low $^{87}Sr/^{86}Sr$ initial ratio of 0.7041+/-1, and combined Sr and Pb isotopic evidence is consistent with an entirely mantle derivation (van Breemen *et al*. 1979) and therefore is unrelated to the decompression granites. Furthermore, The Glen Dessary syenite, intruded into the Northwest Highland terrane was tectonised during the Scandian episode (see below), the decompression granites from the Grampian terrane were not.

During the period 457 to 449Ma, the Southern Uplands terrane records the deposition of Barrovian metamorphic (plus volcanic arc) detritus into an accretionary prism: detrital garnet has the same 470Ma Sm-Nd age as detrital mica $^{40}Ar/^{39}Ar$ ages (Kelley & Bluck 1989, Oliver 2002), the same as garnet (Oliver 2002) and mica ages (Dempster 1985) from the Grampian terrane indicating Grampian terrane provenance. Grampian terrane mica Rb/Sr and K/Ar cooling ages imply that Grampian terrane uplift coincided with erosion and deposition into the Southern Uplands accretionary prism (Hutchison & Oliver 1998). On the basis of this Oliver (2002) suggested that the ~450Ma post-tectonic S-type granites would have been formed during decompression melting of the Grampian continental crust as it was eroded and exhumed. If the 70km thick Grampian terrane crust was returned to a normal 35km thickness between 465 and 440Ma then the erosion rate would have been 1.4 mm/yr (Figure 4b).

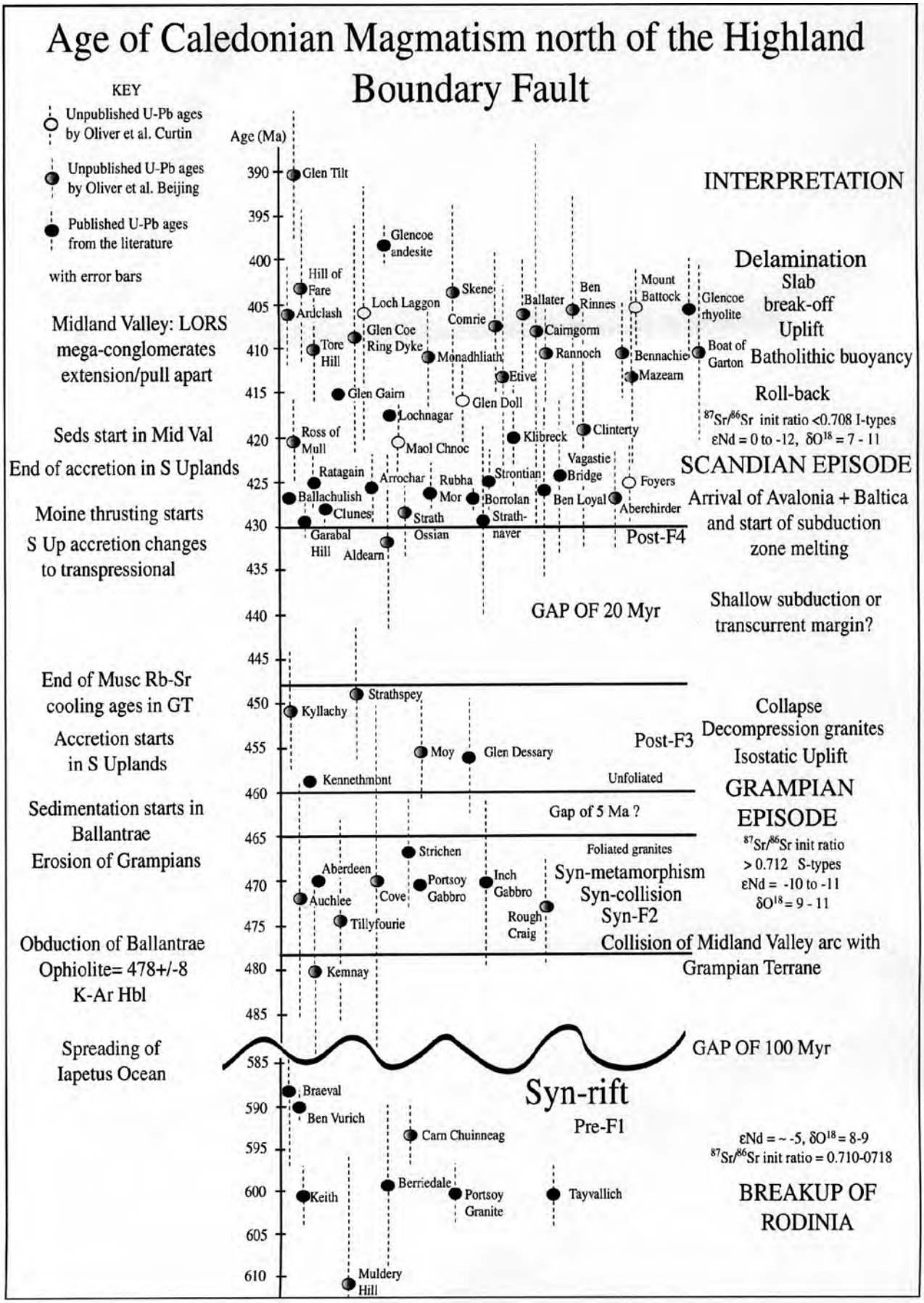

Figure 3. Neoproterozoic and Caledonian magmatism north of the Highland Boundary Fault: ages grouped by age according to Table 1 and Figure 2, with notes on isotope geochemistry, activity in neighbouring terranes and comments on the regional tectonic environment.

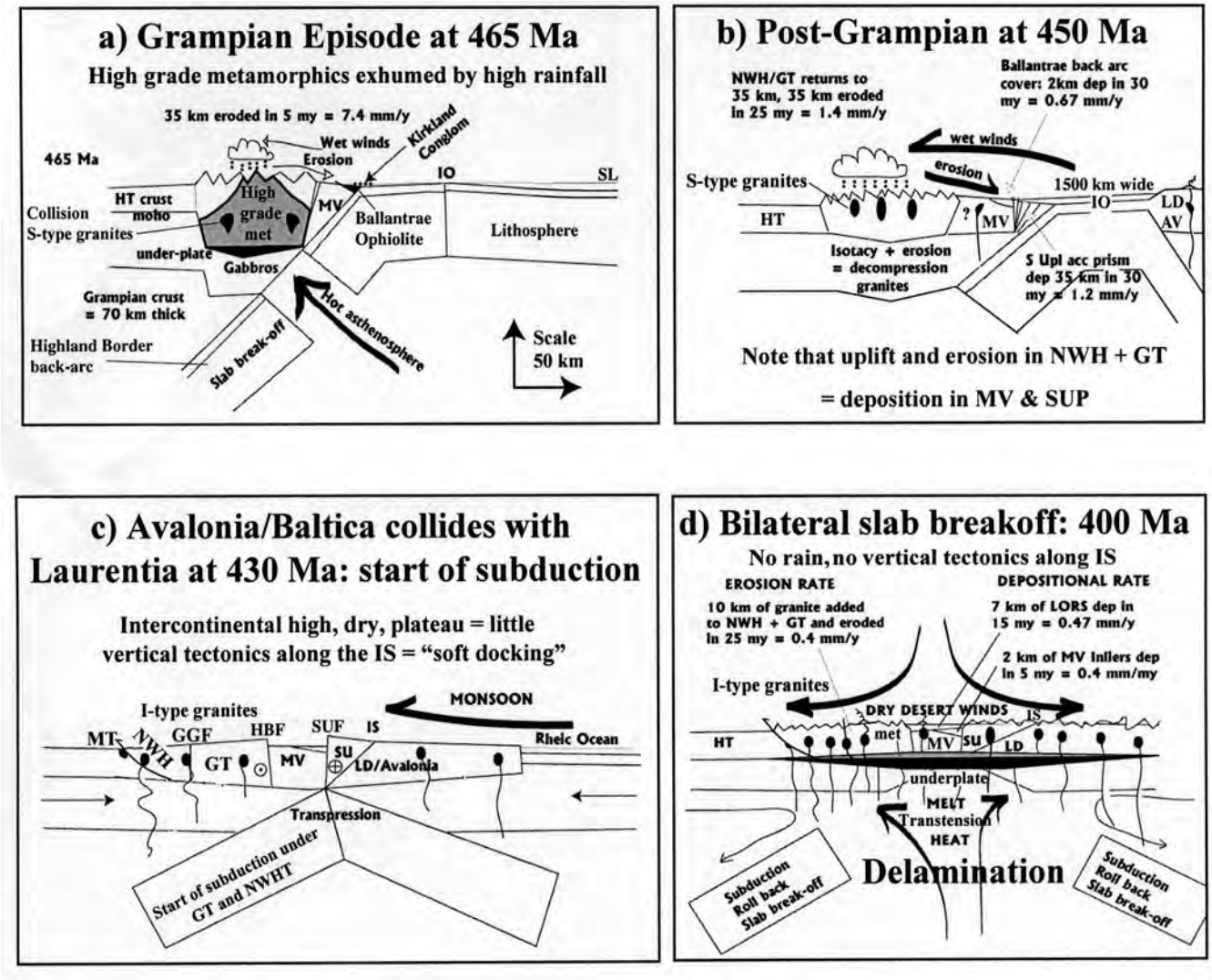

Figure 4. Model lithospheric cross-sections through the Scottish region. (a) Grampian episode at 465 Ma, (b) Post-Grampian at 450 Ma, (c) Avalonia/Baltica collides with Laurentia at 430 Ma, (d) Bilateral slab break-off at 400 Ma. Abbreviations as in Figure 1, black shading basalt underplate, grey shading high grade regional metamorphism.

According to McKerrow *et al.* (1977) the Southern Uplands accretionary prism was built up on oceanic crust during 456 to 423Ma. The crust under the Southern Uplands is now a normal 35km thick (Hall *et al.* 1984), thus ~35km of sediments were accreted between 456 and 423Ma at a depositional rate of 1.2mm/yr, balancing the erosion rate of the Grampian terrane. The accretionary process requires that there was northerly directed subduction, yet there is no in situe evidence of subduction zone granites forming at this time in the Grampian terrane. Hornblende granite boulders with 451Ma Rb-Sr whole rock mineral ages in conglomerates overlying the Balantrae ophiolite are circumstantial evidence for subduction under the Midland Valley at this time (Longman *et al.* 1979) (Figure 4b).

Figures 2 & 3 show another gap in granite activity in Scotland between 450 and 430Ma. Since the Southern Uplands accretionary prism was still active during this time, northward subduction would have continued. The lack of granite activity between 450 and 430Ma suggests that either subduction was at too shallow an angle to cause granite formation, or that subduction rates were so slow that the slab had not had the time to reach under the Grampian terrane. Alternatively, the Laurentian margin was similar to present day western California: i.e. largely transcurrent.

430-420Ma: Scandian episode, start of subduction granites

At 430Ma there was a sudden invasion of Newer Granites (Figures 2 & 3). These are calk-alkaline hornblende and biotite granites which strongly contrast with the earlier ones: i.e. εNd 0-12, $\delta^{18}O$ 7-11 and $^{87}Sr/^{86}Sr$ initial ratios <0.708 (Harmon *et al*. 1984), typical of I-type granites from many modern day continental arcs (Thirlwall 1988). I-type granites are defined as those that were melted from igneous protoliths (Chappell & White 1974). Modern day arc granites are genetically linked to active subduction zones so it is concluded that these Newer Granites date subduction under the Grampian and Northwest Highland terranes.

The Rogart (Soper 1963), Borrolan (van Breemen *et al.* 1979), Strontian (Hutton 1988), Garabal Hill (Rogers & Dunning 1991), Ratagain (Hutton & McErlean 1991), Loch Loyal (Holdsworth *et al.* 1999), Clunes (Stewart *et al.* 2001) and Vagastie Bridge, Kilbreck, Strathnaver (Kinny *et al*. 2003a) intrusions were all controlled by active (mostly sinistral) strike-slip faults or westerly directed thrust zones. This is the time of the sinistrally transpressive Scandian episode of the Caledonian Orogeny when Baltica collided with Laurentia which initiated the Sgurr Beag, Naver and Moine Thrust systems (Kinny *et al.* 2003a, Dewey &

Strachan 2003), and when accretion in the Southern Uplands changed from orthogonal to sinistrally transpressive (Anderson 1987). Sedimentation continued in the Southern Uplands accretionary prism and spilled over into Lake District Windermere Group, implying that Iapetus was still open but that the leading edge of the Lakesman terrane was sliding under southern Scotland (Soper *et al.* 1992). The Caradocian Borrowdale, Ashgillian Stockdale and associated volcanics and Llandovery through to Ludlovian K-metabentonites in the Lake District (Millward 1999) are evidence for a contemporaneous southerly dipping subduction zone under Northern England from 450 to 420Ma (Figure 4c).

420-400Ma: Slab roll-back, slab break off and lithospheric delamination

Sedimentation in the Southern Uplands accretionary prism ceased at 420Ma indicating that northward subduction under Scotland stopped when Avalonia (i.e. the Lakesman terrane) finally docked against Laurentia along the Iapetus Suture. A lack of penetrative foliation in the youngest Southern Uplands sediments signifies that this was a soft docking. At the same time, Old Red Sandstone fluvial sedimentation started in extensional basins in the Midland Valley (Marshall *et al*. 1994). Extension might have been initiated when the subduction zone rolled back and finally broke off by 400Ma (Figure 4d). About 80% of the volume of exposed granite in the Grampian, Southern Uplands and the Lakesman terranes appears to been intruded between 410 and 405Ma. Figure 1 and Table 1 show that this climax of granite intrusion coincides with voluminous calk-alkaline subduction-related andesite volcanism in the Midland Valley (Thirlwall 1988). This temporal correlation across the Iapetus Suture suggests that both the northward and southward dipping subduction slabs broke off at the same time, effectively delaminating the lithosphere under Scotland and northern England, allowing hot asthenosphere to well up. Rising asthenosphere would partially melt during decompression forming a basalt magmatic underplate. The subduction-related magmas in this model (Figure 4d) may have evolved from this basalt magma by fractionation and contamination at the base of the crust (Davidson & Arculus 2001). Positive εNd and low $^{87}Sr/^{86}Sr$ (<0.706) initial ratios suggest relatively uncontaminated mantle magma sources whilst negative εNd isotopic compositions (-5 to -12) and inherited zircon indicate mantle magma mixing with melted continental crust (Harmon *et al.* 1984).

Stephens & Halliday (1984) have distinguished the Argyll, Cairngorm and South of Scotland suites on the basis of chemical and isotopic criteria (see Figure 1b). These different suites possibly reflect the different nature of the lower crust under these regions. Palaeoproterozoic Rhinns-type crust underlies the Argyll suite (Dickin & Bowes 1991), Neoproterozoic Knoydartian crust probably underlies the Cairngorm suite (Oliver *et al.* 2000), whilst Palaeozoic Lakesman crust underlies the Southern Uplands (Soper *et al.* 1992, Anderson and Oliver 1996). The Fleet and Criffel plutons in the Southern Uplands have muscovite-bearing granite varieties with $^{87}Sr/^{86}Sr$ initial ratios up to 0.7109 and $\delta^{18}O$ up to 12, (i.e. transitional S-type) attained either by strong fractional crystallization of mantle-derived magmas and/or melting of the local Silurian greywackes (Stephens 1992).

410-405Ma: batholithic buoyancy of the Grampian terrane

From Figures 1 and 2 it can be seen that ~80% by volume of Newer Caledonian granite in the north-eastern Grampian terrane was intruded between 410 and 405Ma. The effects of batholithic buoyancy on terrane uplift due to the reduction of crustal density with granite emplacement has been explored by R. Robinson (pers. comm.) using a 2-D flexure model. The buoyancy effect of this additional granite would have (in the absence of erosion, and assuming average crustal and mantle densities) raised the surface of the central section of the Grampian terrane by about 2.6km. The period 410-405Ma coincides with the period of maximum Lower Old Red Sandstone alluvial fan conglomerate deposition in the Midland Valley. These conglomerates are dominated by contemporary Midland Valley andesite, Grampian terrane Barrovian metamorphic and Grampian terrane granite debris. As much as 5km of Lower Old Red Sandstone was deposited in extensional and pull-apart basins (Marshall *et al*. 1994). Thus there is a link between Grampian terrane granite intrusion, buoyancy driven uplift, erosion and deposition in the neighbouring Midland Valley. The Highland Boundary Fault would have been active at this time. This is orogenesis by definition (i.e. mountain building) driven by subduction and not collision.

Scottish climate and plate tectonics between 500 and 400Ma

Figure 5 displays World palaeogeographic reconstructions from 500 to 400Ma based on palaeomagnetic and faunal evidence (Cocks & Torsvik 2002). The prevailing wind belts have been superimposed according to the present day equinox patterns. The assumption is that there would have been similar convection cells as today with a low pressure equatorial convergence zone, high pressure subtropical divergence desert zones at 30° N and S, and low pressure convergent zones and polar fronts at 60° N and S (Marshak 2001). Added to this would be the monsoon effects of large land and ocean masses.

The interactions of climate and convergent plate tectonics have been modeled by Willet (1999). The compressive force of plate convergence is balanced by a combination of tractional forces at the junction of the sliding plates and the gravitational force of the rising orogenic wedge. Convergence leads to crustal thickening and isostatic uplift. In the absence of erosion (i.e. desert conditions) the wedge will thicken and a plateau will be uplifted until it reaches an equilibrium elevation of ~7 km. With further convergence the plateau will widen e.g. Tibetan Plateau (Beaumont *et al.* 2001) and the Altiplano (Lamb & Davis 2003). However, increased elevation perturbs local climate, increasing precipitation and erosion. Precipitation and erosion will be focused on the windward side of an orogenic wedge, so much so that in certain situations e.g. west coast of the South Island, New Zealand (Willet 1999) and the High Himalaya (Beaumont *et al.* 2001) climate can focus tectonic activity resulting in the exhumation of high grade metamorphic rocks. These effects of erosion on the structure of mountain belts will now be applied to the Caledonian history of Scotland.

Scotland at 500Ma

At ~500Ma Laurentia lay astride the equator with Scotland positioned on its southern passive margin at 25° S (Figure 5a). To the south the Iapetus Ocean was ~3000km wide. Assuming that the World's axial tilt was the same as today's, then during the Southern Hemisphere's winter the equatorial convergence zone would lie north of the equator and dry north-westerlies would prevail over Scotland. In the Southern Hemisphere's summer period,

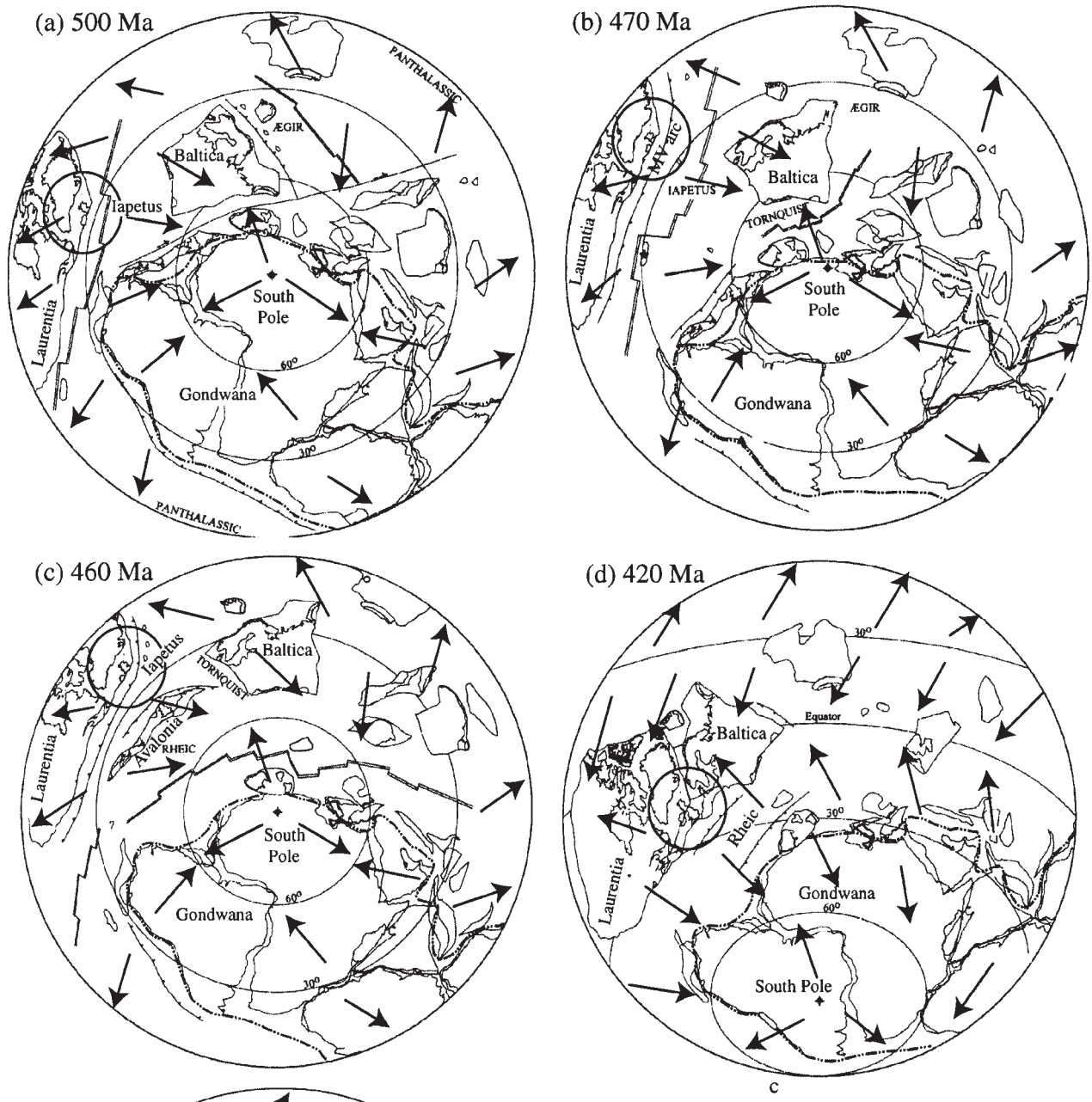

Figure 5. Plate reconstructions (after Cocks and Torsvik 2002) with Scotland highlighted inside circle. Arrows indicate superimposed present day equinoctial wind belts. Each diagram shows Scotland at :

(a) 500 Ma: passive margin, dry NW winter and wet SE summer monsoons, little erosion.

(b) 470 Ma: Grampian collisional episode, dry NE winter and very wet summer SE monsoons, with massive erosion.

(c) 460 Ma: active margin, dry NW winter and moderately wet SE summer monsoons, moderate erosion and decompression melting.

(d) 420 Ma: Scandian episode, beginning of subduction, less rain, less erosion, less vertical tectonics.

(e) 400 Ma: shaded = major continental land masses, batholithic buoyancy, high LORS desert plateaux.

the equatorial convergence zone would lie south of the equator and wet south-easterlies would be sucked in from the Iapetus Ocean. As this margin of Laurentia was passive with no plate convergence, there might not have been much relief.

Scotland at 480-470Ma

By ~470Ma Laurentia had drifted north and Scotland was at Lat 20°S when the Midland Valley arc collided with southern Laurentia (Figure 5b). Barrovian metamorphism and granites and gabbros formed during crustal thickening and slab break-off. Wet summer monsoonal south-easterlies would continue to come in off the ~4000 km wide Iapetus Ocean. During collision high mountains would have formed over the Grampian terrane and orographic rain would focus fast erosion and fast exhumation of high grade Barrovian metamorphics in a narrow orogenic wedge (Figure 4a). The situation might have been analogous to the modern day Himalaya where tectonics, metamorphism, magmatism and climate all interact (Beaumont *et al*. 2001, Zeitler *et al.* 2001).

Scotland at 460-455Ma

By 460-455Ma Scotland was still at 20° S whilst Avalonia had separated from Gondwana and drifted north, reducing the width of Iapetus to ~1500km but opening up the Rheic Ocean behind thus perhaps moderating the wet summer monsoon over Scotland (Figure 5c). The Laurentian margin was no longer active and erosion gave rise to isostatic decompression melting in the lower crust forming more granites (Figure 4b). Deposition started in the Southern Uplands at 455Ma.

Scotland at 430-420Ma

Between 430 and 420Ma Scotland was still at 20° S (Figure 5d). The Laurentian margin became active again as granites were accreted during subduction of Iapetus oceanic crust and the leading edge of Avalonia (Figure 4c). Collision with Baltica caused the Scandian orogenic episode in the Northwest Highland terrane. Limited summer monsoon rainfall coming in off the Rheic Ocean gave rise to a wide orogenic wedge with little vertical tectonic activity over the Iapetus Suture zone. Fluvial Old Red Sandstone facies were deposited in the Midland Valley.

Scotland at 400Ma

By ~400Ma Scotland had become part of a large continental land mass (Figure 5e). Scotland had drifted to 30° S to lie under the dry subtropical high pressure cell: 410-405Ma was the time of maximum granite intrusion during lithospheric delamination following bilateral slab roll-back and break-off. Batholithic buoyancy lifted a high, dry, wide, Lower Old Red Sandstone desert plateau over Scotland and northern England as more and more granites were accreted. Alluvial fans were deposited in the Midland Valley. The crust either side of the Iapetus Suture may have thickened during convergence and high grade metamorphic rocks may have formed in the lower crust. However, the lack of precipitation, erosion and exhumation prevented the exposure of these metamorphic rocks (Figure 4d).

Conclusion

The Caledonian orogeny in Scotland is composed of the Grampian and Scandian episodes. Without the pitter-patter of raindrops there would have been no deep erosion of high grade Barrovian metamorphics, no decompression granites, no Southern Uplands accretionary prism, and no Lower Old Red Sandstone terrestrial facies. Because of the lack of rainfall, the Iapetus Suture zone did not develop into a significant orogenic feature.

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Book reviews

Classic Landforms of the Loch Lomond Area by David J.A. Evans & Jim Rose, 2003, Geographical Association, 160 Solly Street, Sheffield. S1 4BF, 56pp £9.99, (paperback) ISBN 1843770725.

For such a brief booklet this publication is crammed full of useful information, geological maps and delightfully scenic illustrations. The aim of the Classic Landforms series is to make modern explanations of these classic landforms available to all, and I imagine anyone with even just passing interest in landscapes and the processes that create and modify them would find these booklets extremely useful when they decide to go out and get some hands on experience.

The reader is introduced firstly to the southern Loch Lomond basin and given a brief overview of how geological processes have shaped the area since the Precambrian, including the not insignificant effects of the development of the Highland Boundary Fault, and the subsequent emplacement of Cambrian and Ordovician marine rocks, and Devonian sands. However it is the pre-glaciation drainage patterns of the Tertiary, governed by varying altitudes and rock type, and the periods of glacial erosion and thaw, of the Quaternary period, and the rising and falling shorelines that has produce the landscape we see today. Charts and diagrams illustrating these processes are abundant. All aspects of the land forming processes are covered including isostatic rebound, climate, vegetation, marine transgression, cirques, moraines, kames just to mention a few. What I like especially is that the maps, and clearly stated access information given at the end of each chapter, make you want to hastily reach for your rucsac and boots.

Subsequent chapters describe the effects of, and present day evidence for glaciation in other nearby localities of interest to the geomorphologist such as the Campsie Fells, Conic Hill, Drumbeg and Gartness, Croftamie, Cameron Muir, and the Endrick Water Floodplain. The Loch Lomond area has long been the playground of Glasgow's geologists, walkers and climbers; it's only a short train ride or car journey from the city, and perhaps this book will go some way to enhancing local peoples knowledge of what lies on their own doorstep.

Stuart Fairley, OUGS West Scotland

An introduction to the Solar System by Neil McBride & Iain Gilmour (Eds), 2004, Cambridge University Press, 412pp, £30.00 (paperback) ISBN 0521546206, £75.00 (hardback) ISBN 0521837359.

With a cover photograph of my favourite solar body, Io, this book couldn't fail to attract my attention.

It explores and demonstrates the processes which make our solar system function and is supported throughout, by stunning photographs and detailed line drawings.

Essentially a teaching book for undergraduates it forms part of the OU course, S283 Planetary Science and the Search for Life.

As expected, it is clearly written and a joy to turn over each page. A fascinating fact or a thought-provoking statement is on each page.

This book covers such a wide range of information that there is bound to be something for anyone who has ever had an interest in what is beyond our planet. It claims to appeal to amateur enthusiasts and undergraduates.

Written with the student in mind, there are in - text questions in the OU style.

Unless you are actually doing the course, then it can be treated as a reference book. It represents, to my mind, excellent value for money with so much knowledge available for each penny spent!

Yvonne Lewis-Cutt BA Hons (Open)

The geology of the Caledonian Foreland and Moine Thrust Belt: new thoughts on old rocks

Dr Iain Allison[1] & Dr John Mendum[2]

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[2]British Geological Survey, Edinburgh

The abstract that Con Gillen wrote for his talk is remarkably close to what John and I will talk about. I shall give an overview of the geology of the NW foreland and John is going to present the modern data and interpretations.

This is obviously a talk for the Open University Geological Society, but really it is a talk by the Open University Geological Society because all the photographs that you will see were taken on two OUGS excursions. Ian Dalziel started with the word 'plagiarism' across the screen. I have a very simple view of plagiarism: you always credit your source; you can be accused of copying but you cannot be accused of plagiarism and I am very grateful to Lynn Everson for all the photographs used in this talk.

We start with a classic view of the NW foreland with the peneplained surface of the Lewisian gneisses from which rise the magnificent mountains of Torridonian sandstone, for example, the mountains of Suilven and Canisp (Figure 1).

Figure 1. The mountains of Suilven (centre) and Canisp (left).

In map view the Moine Thrust may be traced from the north coast south-south-west to the Isle of Skye (Figure 2). The area I am going to be talking about is the Caledonian Foreland to the west of the zone of complication which underlies the Moine Thrust and is a belt up to 12 km wide immediately to the west of the thrust. Here the rocks of the foreland are all sliced up and stacked one on top of the other. Further west is what we might call the stable foreland with a metamorphic basement, the Lewisian Gneiss Complex, overlain by a layer-cake sedimentary stratigraphy of late Proterozoic and Cambro-Ordovician age.

An excellent place to start is at Knockan Cliff where a sculptor's view of the stratigraphy is depicted in a stone wall (Figure 3). At the bottom, the Precambrian gneiss is overlain by the Torridonia sandstones, which are in turn overlain by a succession of Cambrian rocks. These start with cross-bedded quartz-arenite at the base grading up into quartz-arenite with a lot of bioturbation in the form of vertical tubes – the so-called Pipe Rock. These are commonly interpreted as infilled worm tubes. Above that is a sequence of dolomitic shales and shaly dolostones, the Fucoid

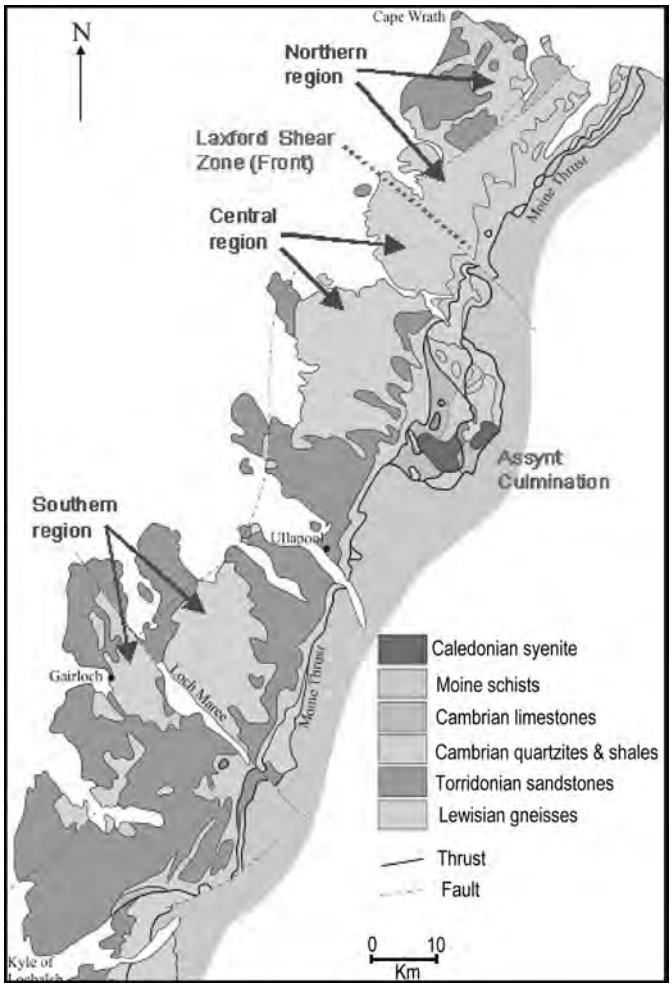

Figure 2. Geological map of north-west Scotland.

Beds, so called because the horizontal worm burrows resembled seaweed impressions. Next there is a thin quartz-arenite often with a small conical fossil, Salterella, hence the name Salterella Grit and overlying that is a thick sequence of mainly dolostones,

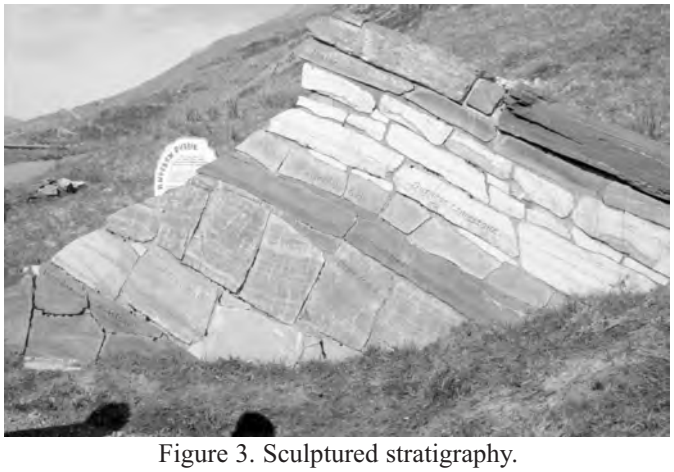

Figure 3. Sculptured stratigraphy.

the Durness Carbonates. On the trail at Knockan Crag the sequence from the Pipe Rock to the base of the carbonates is well displayed. Above a few metres of carbonate the Moine Thrust itself is well exposed and above it is a thick sequence of quartz-rich mylonites which grade up into the Moine Schists - the metamorphic rocks of the Caledonian mountains which have been thrust westwards onto the foreland. Here there is no belt of complication; however, a couple of kilometres north at Assynt the zone of complication is some 12km wide.

The Lewisian gneisses: the simple story is that there are two complexes, an older Scourian complex and a younger Laxfordian complex, separated by a distinct time marker called the Scourie dykes. Where the Scourie dykes are relatively undeformed and retain their dyke-like character even though their mineralogy is that of a metamorphic rock we refer to these gneisses as Scourian. Where these basic doleritic sheets have been deformed, boudinaged and smeared out into parallelism with the gneissic layering these are Laxfordian gneisses. There are also other igneous rocks within these complexes. In South Harris original igneous rocks ranging in composition from gabbros to anorthosite have now all been transformed into gneisses and have developed a foliation as well as metamorphic minerals. In some of these rocks well-developed shear zones occur. In these zones the strain increases rapidly from the edge to the centre and the original gneissic layering is overprinted with a much accentuated new fabric and a finer-grained mineral assemblage.

The time marker between the Scourian and Laxfordian is a suite of dykes, the Scourie dykes. We usually expect igneous bodies to be upstanding and more resistant than the surrounding rocks. At Scourie, the thick dyke which has given its name to the suite is the opposite; it occurs as an in-weathered gap between the gneisses. In the basic igneous rocks all gradations exist from sharp discordant margins with the Scourian gneissic layering through slight pinch-and-swell structures and boudinage to complete parallelism with the gneissic layering.

The rocks and structures of the Laxfordian gneisses are excellently exposed in road cuttings at Laxford Brae, just north of Loch Laxford (Figure 4). Here the road cuttings, formed by the technique of pre-split blasting which gives very clean planar surfaces, show the grey gneisses, the dark, deformed remnants of Scourie dykes and later cross-cutting granite pegmatites. The age relationships are easily worked out.

Figure 4. Gneiss exposure. in road cuttings at Laxford Brae

Overlying the Lewisian are two sequences of Torridonian red sandstone of late Precambrian age: the lower Stoer Group is about 1,100Ma old and the Torridon Group about 1,000Ma. At Enard Bay the Lewisian unconformity surface beneath the Stoer Group is visible and some people have interpreted it as a periglacial surface as there are a lot of broken blocks. Coating the hummocky surface is the lowest layer of the Stoer Group: red laminated algal limestones which have formed on top of the very irregular surface. The Stoer Group has an angular unconformity with the Torridon Group and as both successions are of red sandstones the difference between them was not recognised for many years until palaeomagnetic work gave different palaeolatitudes for their formation.

Figure 5. Slioch and Loch Maree.

The Torridon Group sandstones are a thick sequence of terrestrial red beds that form many of the spectacular mountains in the north-west, for example, Slioch (Figure 5). Overlying them with an angular unconformity of almost 20° is the Cambro-Ordovician succession. As the unconformity dips east the Torridonian sandstones are eventually cut out so that in the eastern part of the foreland the Cambrian rests directly on the Lewisian gneisses. The base is marked by a thin conglomerate and is overlain by a sequence of over one hundred metres of quartz-arenites. The unconformity is clearly visible on the north coast just east of Durness (Figure 6). Here the Lewisian gneisses have a different appearance. The grey and red of the gneisses is replaced within a metre or two of the unconformity by a pale green rock which retains all the character of the gneisses but is much softer. My interpretation is that this is the lowest part of a weathering profile on top of the gneisses and this rock is now all muscovite. This was recognised by Peach and Horne in their original geological survey of this area. Deep tropical weathering in late Precambrian times converted the rock to clay minerals. Now only the lowest parts of this profile are preserved and subsequent burial beneath the Cambrian rocks has converted the clays to muscovite.

Figure 6. The Cambrian unconformity just east of Durness.

Above the quartz-arenites, the dolomitic shales of the Fucoid Beds ends with a layer of splintery shale, or argillite, which is composed largely of a sedimentary feldspar, adularia, and gives these shales a potash content of up to 12%. These rocks have been used as a soil amendment in organic agriculture. Above the Fucoid Beds the thin Salterella Grit gives way to the Durness Carbonates. The lower part of this sequence of mainly dolostones contains a variety of interesting sedimentary structures. Layers scattered with aeolian, 'millet-seed' sand grains testify to sand dunes on the landward area to the west. Small, narrow, steep-sided channels were formed by rip currents going back down the shelf beneath a stormy sea. Chert concretions within the carbonates form a sort of cauliflower shape with distinctive black and white laminations spreading up and outwards from the central part (Figure 7). The laminations are from algal stromatolites and the spherical mass of chert has nucleated where the stromatolites join.

Figure 7. Chert concretions within carbonates.

In the Assynt region, these carbonates with their chert nodules have been converted into marbles which can be seen near Ledmore junction and at the Ledmore North marble quarry (Figure 8). Here the intrusion of basic igneous rocks at the end of the Caledonian orogeny has converted the dolostones to marble and where there are cherts a sequence of complex calcium-magnesium-silicate minerals occurs and indicates temperatures of contact metamorphism up to 900ºC. The interplay between intrusion and thrusting allows us to date some of the events in the thrust belt and for these and other details I now past on to John Mendum.

Figure 8. Ledmore North marble quarry

I am going to rapidly run through some recent work which has been done at the British Geological Survey on the Moine Thrust Belt and then give a brief review of Clark Friend's work on the Lewisian Gneiss Complex. This is based partly on a lecture previously given by my co-author, Kathryn Goodenough who is not here, but those of you who go to Glen Coe tomorrow will come across her. Thank you, Kathryn.

We are going to be talking about the Assynt Window, the Foreland area, and making brief visits to the Outer Hebrides. On the geological map the Lewisian rocks are coloured pink, the overlying Torridonian rocks grey-brown. The Assynt Window or Culmination is unusual in that it exposes a structural thickness of between 2 and 3 kms in the Moine Thrust Belt; normally the rocks of the thrust belt are only tens or at most hundreds of metres thick.

Two Victorian gentlemen, Ben Peach and John Horne (Figure 9), did an absolutely stunning job in mapping the geology of Assynt originally in the 1880s. Much of the mapping that they did is still used; we cannot improve on it significantly. Charles Lapworth (Figure 10), working initially in the Eriboll area in the early 1880s, was first to understand the nature and mechanisms operating in the Moine Thrust Belt. He not only got the geology correct, but when they had a government enquiry into the nature of the Geological Survey in the 1890s, he sat on the Board and recommended that the Survey carry on and be reconstituted, reorganised and given more money. So we have a lot to thank him for.

The Assynt area exposes the thrust belt very beautifully. It is a very important structural succession and the work Kathryn has done concentrates on the unusual igneous rocks that form abundant minor intrusions.

Figure 9. John Horne and Ben Peach outside the Inchnadamph Hotel, 1912. Reproduced with the permission of the Director, British Geological Survey, ©NERC.

Figure 10. Charles Lapworth. Reproduced with the permission of the Lapworth Museum of Geology, University of Birmingham.

Basically the Assynt window comprises three main thrust sheets, the Sole Thrust Sheet, the Glencoul Thrust Sheet, and the Ben More Thrust Sheet. The Loch Ailsh and Loch Borralan alkaline complexes intrude the overthrust Foreland rocks: that is the Lewisian Gneiss Complex, Torridonian and Cambrian successions. Movements on the Moine Thrust were initially dated by the age of the Loch Borralan pluton at 430Ma. The intrusion of this pluton was interpreted as roughly synchronous with thrusting and although the U-Pb zircon isotope age is quite an old date, it is still regarded as reliable (van Breemen *et al.* 1979). The intrusion of the Loch Ailsh pluton, which predates the thrusting, is 439Ma (Halliday *et al*. 1987). The mylonites at Knockan and elsewhere in the thrust belt were dated by Freeman *et al.* (1998) using Rb-Sr methods on micas. He obtained ages ranging from 437-425 Ma. Similarly in Sutherland, Dallmeyr *et al.* (2001) obtained Rb-Sr mica ages of 428-413Ma at Faraid Head, again suggesting that mylonitisation accompanied the main movements that occurred during the Silurian-age Scandian event.

Within the Assynt Window and adjacent area are numerous alkaline to calc-alkaline minor intrusions, collectively termed the Northwest Highland Minor Intrusion Suite. They were originally studied in detail by Sabine (1953) and later by Young (1989). Seven different swarms are recognised: they range from lamprophyres to quartz-microsyenites and rhyolites, but all seem to be related and to have a subduction-influenced chemistry. The Canisp porphyry (porphyritic quartz microsyenite) forms thick sills to the west of the Sole Thrust centred on Canisp; crucially, it is not seen within the thrust belt. Ledmorite (melanite augite nepheline-microsyenite) occurs as dykes in the Foreland rocks, but intrusions are also found in the thrust belt where they appear to link to the Loch Borralan pluton. Vogesites, microdiorites and peralkaline-rhyolites are found throughout the thrust belt and seem to predate the main thrusting, but porphyritic trachytes are only found close to the Ben More Thrust and contain some thrust-related fabrics. In contrast the nordmarkites (quartz microsyenites) seem to straddle either side of the Moine Thrust itself with some intrusions occurring in the Moine succession. If the various minor intrusions can be dated accurately they should give a time frame for the main thrusting in the Assynt Window.

The recent work has shown minor improvements to the abundance and occurrence of the minor intrusions. In particular the peralkaline rhyolites are now recognised to be more abundant. Specimens were collected for dating from the places shown and passed to NIGL for separation of zircons and dating. As the Canisp porphyry apparently predates movements in the thrust belt, it was a prime target for dating. Jane Evans at NIGL in Keyworth obtained some good U-Pb laser ablation and thermal ionisation (TIMS) zircon ages from some good oscillatory zoned euhedral zircons of apparent igneous origin from this intrusion. The four best TIMS ages gave a pretty accurate date of 436.4 ± 5 Ma with a very small MSWD (0.19) and are plotted on the graph below (Figure 11).

The remaining intrusions, except for the nordmarkites, are interpreted to have been intruded just prior to or in the early phases of thrusting. The Borralan pluton is interpreted to postdate the thrusting, thus bracketing main movements between 436Ma and 430Ma. This is the Scandian deformation event, a manifestation of the Baltica-Laurentia collision to the north of Scotland. Table 1 shows the different intrusions and their relationship to thrusting.

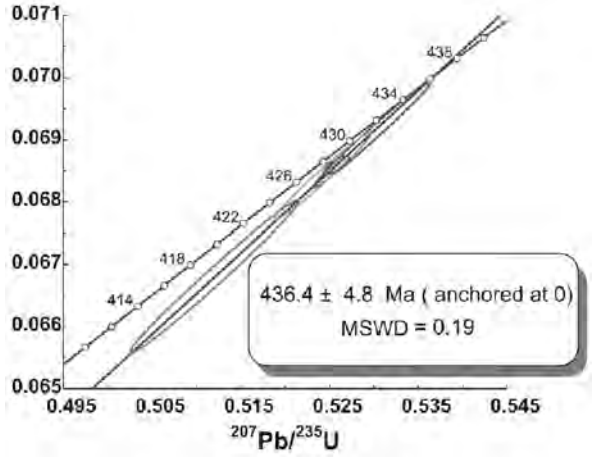

Figure 11. Concordia diagram for conventional TIMS analysis of zircons from KG23 (Canisp Porphyry)

Note that the lowest thrusts in the culmination are the latest to form and carry the earlier formed thrust material 'piggy-back' to the WNW. At Knockan the Moine Thrust appears to be a late structure (out-of-sequence thrust or extensional fault) and does not follow the normal 'rules' of thrusting. The nordmarkites remain a problem as they give a considerably older age, yet appear to relate geochemically to the other intrusions. The nature of any earlier movement has still to be established. Although we have apparently dated the Scandian movement, what happened in the Grampian or the older Neoproterozoic orogenies still remains enigmatic. These orogenic fronts must be buried beneath or incorporated within the later Scandian orogenic front.

Table 1. Assynt intrusions and their relationships to thrusting.

Intrusion	Structural relationships	Age
Loch Borralan Pluton	Cuts Ben More Thrust	430±4Ma
Porphyritic Trachyte Swarm	Possibly cuts foliations related to Ben More Thrust	
Main movements in the Moine Thrust Belt		
Peralkaline Rhyolite Swarm	Cuts hornblende microdiorites and Loch Ailsh syenites. Folded by thrust-related folds	
Hornblende Microdiorite Swarm	Folded by thrust-related folds and deformed approaching Moine Thrust	
Vogesite Swarm	Imbricated by thrusts within the Moine Thrust Belt	
Canisp Porphyry	Only seen W of Sole Thrust and thus considered to predate movement on this thrust	436.4± 4.8Ma
Loch Ailsh Pluton	Deformed by movement on Moine Thrust	439±4Ma
Possible early movements on the Moine Thrust?		
Nordmarkite Swarm	Deformed by movements on Moine Thrust but apparently concentrated along the thrust	~485-515Ma

Now I will pass on to the rocks of the Lewisian Gneiss Complex of the Foreland. Peach and Horne (Peach *et al*, 1907) recognised three main regions in the Lewisian (Figure 2): a Southern Region which is geographically separate, and a Central Region and the Northern Region, which are separated by the Laxford Shear Zone or the Laxford Front. A summary of recent age data shows that the Northern Region contains evidence of pervasive Laxfordian metamorphism, the Central Region shows evidence of earlier Archaean metamorphism and deformation with only local evidence for later reworking, and the Southern Region again shows significant Laxfordian reworking. The earlier Archaean Scourian events are separated from the later Proterozoic Laxfordian reworking by the intrusion of the Scourie dykes at around 2400 Ma. Most recent work in the Lewisian rocks has been based on U-Pb zircon and monazite dating and has shown their geological history to be very complicated. The protoliths of the Lewisian rocks formed deep in the Earth's crust and are mainly acid to intermediate plutonic rocks now generally referred to as TTG (tonalite, trondhjemite, granodiorite) gneisses. Zircon and monazite age dates obtained over the past 10 years show that in the Northern Region the TTG protoliths were intruded at *c.* 2800Ma. In contrast in the Central Region, notably around Scourie, the protolith tonalites, etc. have an age of *c.*3000Ma. Farther south around Gruinard Bay TTG protolith ages range from 2720 to 2850Ma, and in the Southern Region they are similar. The later granulite facies metamorphism that is manifest in the Central Region has been dated at either 2700Ma or 2530-2490Ma. Scourie dyke emplacement occurred at about 2400Ma in the early Palaeo-Proterozoic with a later phase at around 2000 Ma (Heaman and Tarney, 1989). The Laxfordian metamorphic overprint, which is everywhere at amphibolite facies, occurred at around 1750Ma; there is only a smidgen of Laxfordian reworking in the Central Region but it dominates in the Northern and Southern regions. The Laxford granites, will be discused later. Clark Friend and Pete Kinny have worked on dating the Lewisian Gneiss Complex over the past 15 years and have produced much new zircon U-Pb age data. Most of this has been obtained from the SHRIMP machine at Curtin in Western Australia. This is valuable work and Clark Friend has used the data to divide the Lewisian into several discrete terranes (Figure 12) that he interprets as having separate early histories and having been later amalgamated to form the existing complex. He has renamed the regions and, dependent on the available data, attempted to draw boundaries to individual terranes. He showed that the Laxford granite was intruded at 1855Ma and our recent mapping has shown that the granite postdates most of the deformation in the Laxford Shear Zone and effectively stitches together the Rhiconich and Assynt terrains of Friend and Kinny. The Uig Hills Granites in SW Lewis and North Harris, thought to be on similar age, have been shown to be 180Ma younger at 1675Ma. Note that Clark has added extra terrains or discrete crustal blocks based on differences in zircon age spectra. Thus, he has added the Gruinard Terrane, which contains the younger Loch Maree metasedimentary and metavolcanic rocks laid down at around 1900Ma, and a Roneval Terrane in South Harris that also contains younger arc-related rocks, this time deformed at around 1870Ma. It is important to note that where Clark has obtained zircons out of quite a lot of rocks he has finer-scale units; conversely, where he has only obtained the odd zircon out of the odd rock we have larger terranes. Subsequently, he published a paper in Greenland describing more detailed work and some of the defined terranes are only a few kilometres wide - in fact some of them are deeper than they are wide.

I had occasion to work in South Harris some years ago, so when a Japanese gentleman called Sotoro Baba did a PhD there in the early to mid 1990s. I was called upon to referee some of the resulting papers. Baba, as everybody now realises, did a thorough and perceptive job describing the metamorphism and history of the Leverburgh Belt metasedimentary and metavolcanic rocks of South Harris. Some of the papers are in the Journal of the Osaka University and thus not readily available, but others are in international journals. Baba identified sapphirine in South Harris in the very high-grade metasedimentary rocks. These rocks are orthopyroxene cordierite garnet sillimanite gneisses (originally pelites/mudstones). In these rocks the so-called M1 first metamorphism took place under conditions of ~800°C, 9 kilobars, equivalent to about 30 kilometres down and very hot. The adjacent meta-igneous rocks of the South Harris Igneous Complex show mineralogies compatible with such metamorphic conditions. However, Baba showed that the sapphirine is present, which indicates that the rocks have experienced much higher pressures at a slightly later stage (M2) (Figure 13). Hence, the Leverburgh Belt rocks and the South Harris Igneous Complex must have been down to some 50-60km, probably as a result of rapid subduction. The rocks show partial re-equilibration to lower pressure and temperature conditions with plagioclase coronas, and cordierite alteration. We know from the recent zircon dates that peak conditions were attained at about 1870Ma. Baba produced a tectonic synthesis of the area postulating that it was a small arc-trench terrane with the igneous rocks intruded at the base of the arc and then the whole edifice rapidly subducted and exhumed. The model is widely accepted and was copied by Park for the Loch Maree rocks around Gairloch.

Back to Clark Friend's work. The Roneval terrane is correlated with the Loch Maree rocks as the two situations are similar, but

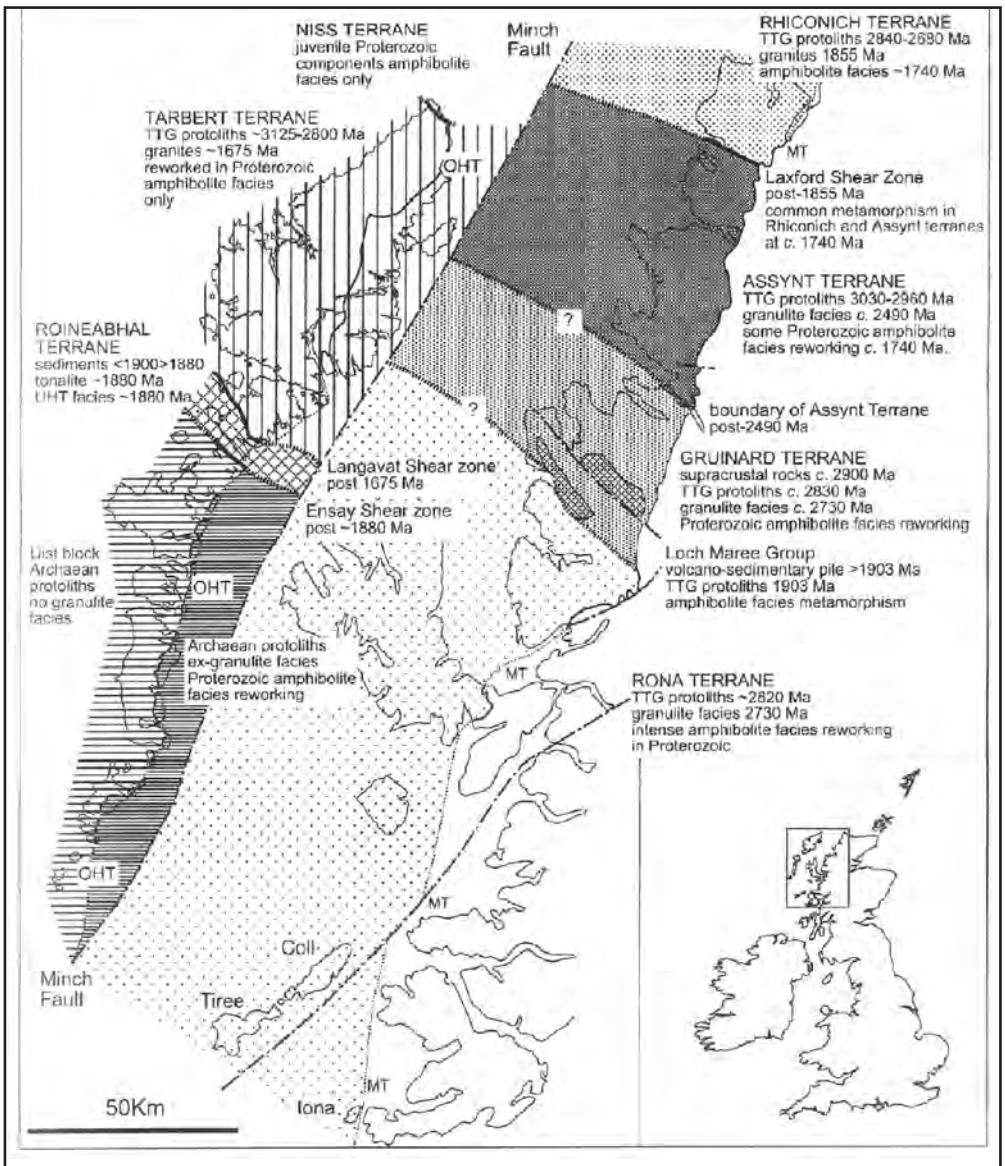

Figure 12. Lewisian terranes in NW Scotland (from Friend & Kinny 2001)

whether they represent two different arc terranes, I do not know. I should add that in the Geological Survey we struggle to use Friend and Kinny's terminology - I do not subscribe to the overall terranes because it involves forming crust at particular periods of time as little blobs. We are talking about events deep in the crust, and then adding another bit of felsic material as a discrete mass - I do not think the world works like that. What Clark has done is try to join up disparate geological areas. However, Friend and Kinny have shown quite clearly that in The Minch there is an earlier suture, not just the Minch Fault, which is a much later structure. This embryo structure is at least 1000Ma old, but it could be considerably earlier given the complex history of the Lewisian rocks. The oldest age in the UK now comes from Scarp in North Harris where TTG gneisses give an age of 3120Ma. Clark tried to join things to East Greenland and there is quite a good match, but I have added the Rockall Plateau, which certainly does contain old basement rocks and complicates the correlation. However, there is a reasonable match and almost certainly the UK was joined to East Greenland, though how and where exactly is problematic in detail. It is important in terms of plate tectonic reconstructions as to how the basement rocks of Greenland and Scotland fit together.

Zircons: everybody is happy to talk about zircons. Most of Clark's zircons from the Lewisian rocks have been SHRIMP dated. Zircons have older cores with younger rims and, depending on how you date them, you get different answers. Zircons are something that everybody really embraces. I remember when potassium/argon dating was god and then Rb-Sr and now it is U-Pb. U-Pb does seem to work quite well in recording when the zircon formed and when the rim formed so these ages can accurately define an igneous event, for example. In metamorphic rocks things are not as clear. If you push a load of fluid through when your rocks are in the base of the crust do you grow another zircon – is that a metamorphic event? Can you have a metamorphic event that is quite dry and does not leave a trace of zircon? If you get different ages from different gneisses, what is it actually telling you? People assume it is a tectonic event, or it is a metamorphic event, but how widespread and important are these events. We have to be a bit careful, so do retain some scepticism and do not take it all as gospel.

Clark has come up with some interesting ages and ideas and progressed our knowledge of the Lewisian gneisses a great deal. His terrane concept may yet prove to be correct. If so the next question, mentioned also by Rob Strachan, is how do the Lewisianoid rocks that form the basement to the Moine succession fit into this pattern? These Lewisian-like rocks have an Archaean history, but are not quite the same as the Lewisian of the Foreland. In the Borgie and Naver Lewisianoid inliers of Sutherland the rocks are more like Lewisian than the Lewisian itself, they have more ultramafics, more Scourie dyke-like bits in them.

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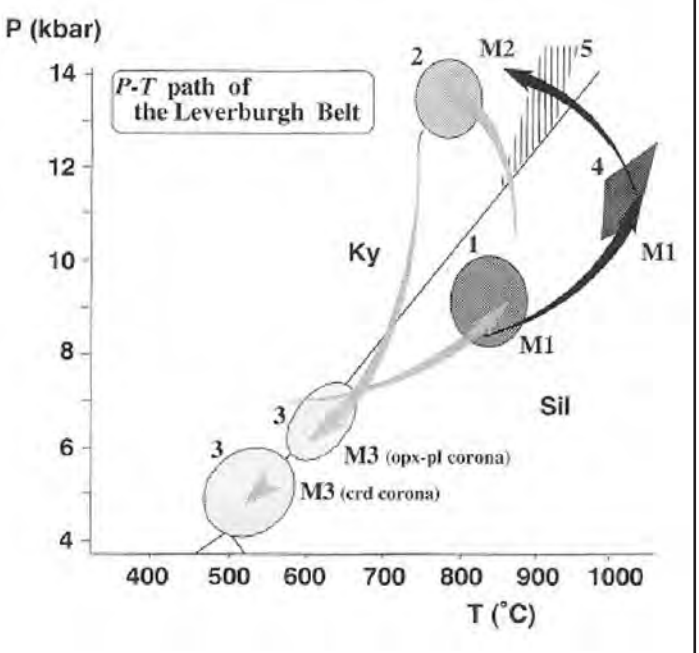

Figure 13. Pressure - Temperature diagram illustrating the metamorphic path taken by the Leverburgh Belt metasedimentary rocks of South Harris (from Baba, 1999).

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Book reviews

Volcanoes of Southern Italy by John Guest, Paul Cole, Angus Duncan and David Chester, 2003, The Geological Society, 284pp, £65.00 paperback, ISBN 1862391386.

In the preface of this book it states that the aim of the book is to provide a wide background to the understanding of volcanoes and their environmental impact through time.

The authors have provided a hugely comprehensive guide to the volcanoes of Southern Italy. The various types of volcanoes are examined and related to examples within the area. I particularly found the section giving the historical perspectives of geological ideas and controversies of scientists and those who showed an interest through detailed studies very informative and interesting. We are given both the geological and geographical background as well as the volcanic and tectonic history and potential volcanic hazard of each volcano in turn. There is a well written description of the geological setting, incorporating stratigraphy, petrogeology and geochemistry of the volcanoes. The authors have also included the human importance and impact of the volcanoes (both historical and recent) and recommend places to visit if you intend to travel to the area.

The area this book covers has been suggested that this is the birthplace of vulcanology, especially as there is a well - documented history of the area. Indeed, I hadn't realised that are 11 volcanoes in the region that have erupted, some extremely violently, at some point in history and there are others, such as Stromboli and Etna, which are in a state of continuous activity and others which appear to have the future potential to erupt at any time.

Throughout the book there are black and white photographs and clear diagrams illustrating points from the text with a section of full colour photographs, chemical composition of some of the volcanic rocks, a comprehensive further reading and reference guide and glossary of terms at the end.

I found this book extremely well written and easy to read. It started with the intention of providing a wide background and the contents certainly seem to provide a "catch all". It provides a very comprehensive guide but at 284 pages is not a pocket guide! If you intend to visit this region or have visited this region, I would suggest this book is a must, however, I do have doubts as to whether a tourist without a geological or geographical background or interest would consider paying £65.00.

Wendy Owens B Sc., B.Ed (Hons.)

Handbook of Atmospheric Science, Principles and Applications, Edited by C N Hewitt and Andrea Jackson, 2003, Blackwell Publishing, 633pp, £150.00 hardback, ISBN 0632052864

At £150.00 this is an expensive and hefty volume of 633 pages. Edited by Nick Hewitt, Professor of Atmospheric Science at Lancaster University, and Andrea Jackson, a lecturer of Atmospheric Science at Leeds University, it draws on the expertise of 28 leading scientific authors.

It is divided into two parts, the first dealing with the principles of atmospheric science, its evolution, energy, chemistry and meteorology. The second part deals with the problems of pollution, monitoring techniques, modelling methods and their application to atmospheric science and the consequence of failure facing the Earth.

Each of the subjects covered by the twenty-one chapters is investigated in great depth and ably reinforced by a multitude of charts, tables and formulae, plus a comprehensive bibliography.

This is definitely not a book for casual reading but, although it is obviously aimed at students on the verge of graduation and researchers, I think it has a lot to offer any science student if they have the funds and patience to take it on.

Mike Steele BSc, Continuing student

The Southern Uplands: new perspectives on an old terrane

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Abstract

Over the last 50 years, research in the Southern Uplands has matured as modern knowledge and techniques have been applied throughout the terrane. The large scale of the area involved has lent itself to the integrated BGS approach involving many geo-specialisms which are available either within the BGS or via associated researchers. This paper brings together some recent research findings which have important implications for understanding the Southern Uplands Terrane.

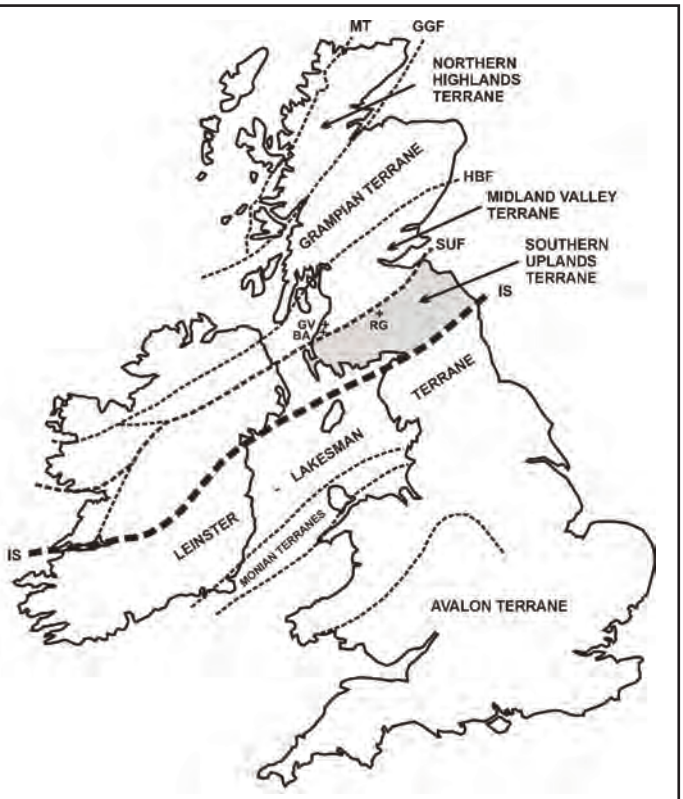

Figure 1. Terrane map of the British Isles, showing setting for the Southern Uplands and adjacent terranes. Abbreviations: BA, Ballantrae; GGF, Great Glen Fault; GV, Girvan; HBF, Highland Boundary Fault; IS, Iapetus Suture; MT, Moine Thrust; RG, Raven Gill; SUF, Southern Upland Fault (terrane nomenclature after Bluck *et al.* 1992).

Terranes

Since the development of the concept of terranes, the Southern Uplands (Figure 1) has been recognised as a good example of a coherent (suspect?) terrane in its own right (Bluck *et al.* 1992). Some researchers have speculated on the presence of different sub-terranes within the southern Uplands but, even if distinguishable, they are of only minor significance. There is little doubt as to the consistency of the geological evolution of the area as a single coherent terrane over a period of *c.*40Ma from at least early Caradoc to Wenlock times (Floyd 2001) as the youngest and most outboard terrane accreted to the Laurentian margin before final closure of the Iapetus Ocean. Consistent with the terrane model, the only potential detailed correlation with a contiguous terrane is with the Girvan area, part of the Midland Valley, and even here the links are fragmentary (Floyd 1999, Ingham 2000).

The basic geological understanding of the terrane has improved by an order of magnitude since Peach & Horne (1899). From the mid-1950s onwards, the 1899 anticlinorium - synclinorium model gradually became unsustainable, principally due to the recognition, through the application of modern sedimentological techniques, of the dominance of thick, northward-younging successions rather than thin, highly folded packets (Craig & Walton 1959). These new interpretations were first developed on the coastal sections of SW Scotland where they were understood to imply a much greater role for thrust faulting (Kellin 1961), dividing the succession into strike-parallel, fault-bounded tracts (Figures 2 and 3). The elegant accretionary prism model (McKerrow *et al.*1977) appeared to explain these tracts and most of the unusual features of the terrane, particularly the 'Southern Uplands Paradox' of the youngest rocks occurring in the south of the terrane despite most sections actually younging towards the north.

From the 1970s onwards, the holistic accretionary prism model was challenged by various competing models (e.g. Stone *et al.* 1987), each trying to account for different apparently incompatible aspects of the geology. However, as evidence has accumulated over the last 30 years, the accretionary prism model has established itself and is probably still the most elegant explanation of the observed geology (Stone & Merriman 2004). Nevertheless, as a result of the proposing and testing of various models for the Southern Uplands, the amount of basic geological knowledge of the area has exploded in the last few decades as almost every available technique has been applied to elucidating the tectonostratigraphy and structure of the terrane. Although many of the niggling problems have been confronted and to some extent overcome, some fundamental issues of stratigraphy and structure are still unresolved, including some relating to correlation and relationship with neighbouring terranes (Figure 1).

Stratigraphy

The basic stratigraphy has remained largely as envisaged by Peach & Horne (1899), though vastly changed in detail. The Crawford Group at the base of the succession has pillow lavas which are considered to represent basalt of the ocean floor or of volcanic islands (Phillips *et al.* 1995). The associated/overlying chert has long been something of an enigma as it was known to contain Arenig fossils at Ravengill, near Abington (Figures 1 and 2). This had potentially profound consequences for the entire terrane as this was considerably older than any other succession in the region. The Ravengill localities have now been re-investigated and Arenig conodonts proven at three localites in the area (Armstrong *et al.* 2002). However, this work has confirmed the long-recognised '10Ma gap' in the succession, with the next youngest chert fauna being of Llandeilian or Aurelucian (earliest Caradoc) age (Armstrong *et al.* 2002, Figure 2). Given this age gap, and its restricted distribution, the Ravengill Formation is now interpreted as an exotic olistostrome from an older basin

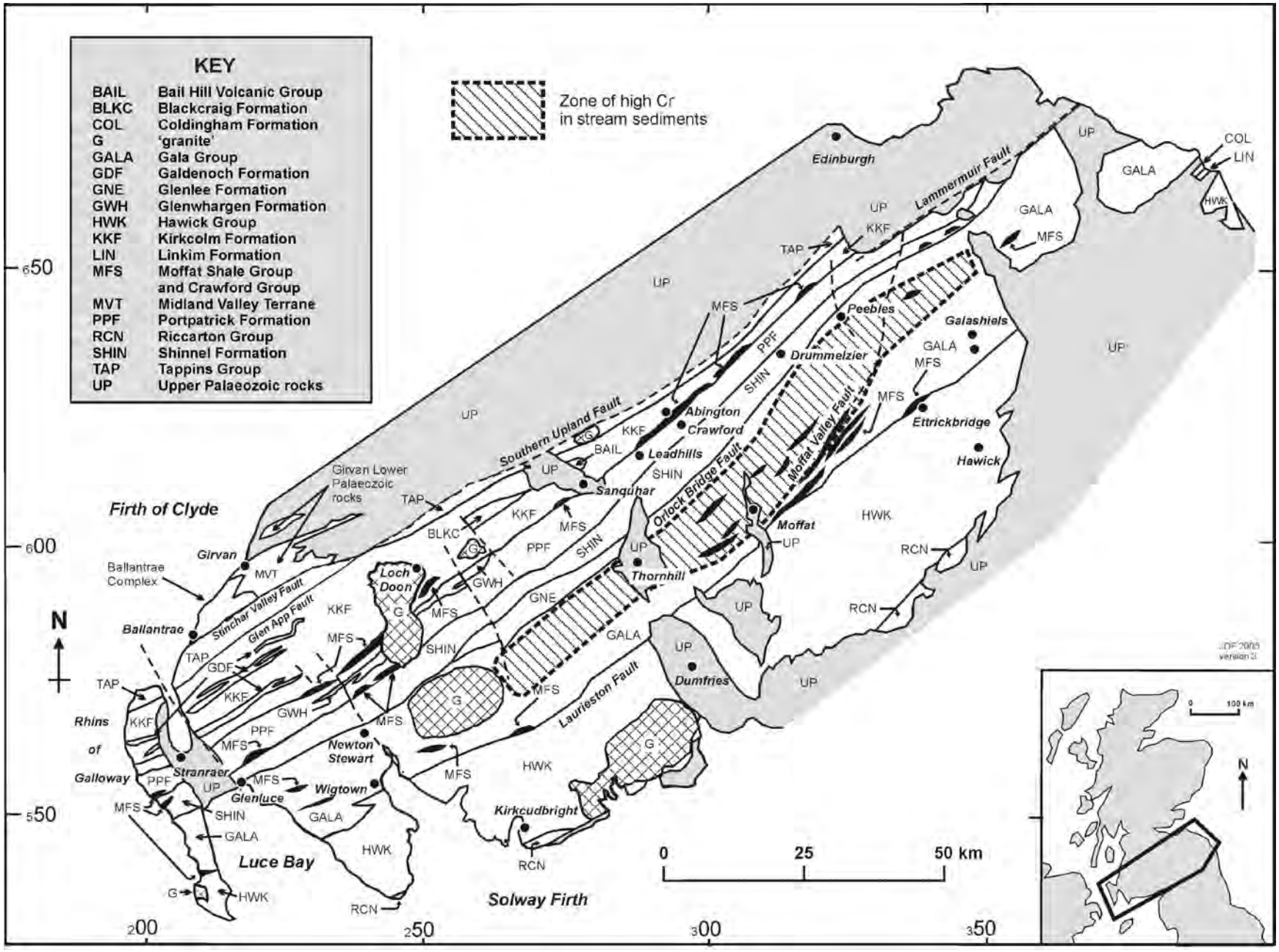

Figure 2. Outline geological map of the Southern Uplands illustrating the extensive strike-wise continuity of tectonostratigraphial units. The zone of high Cr in stream sediments from within the Gala Group is also marked.

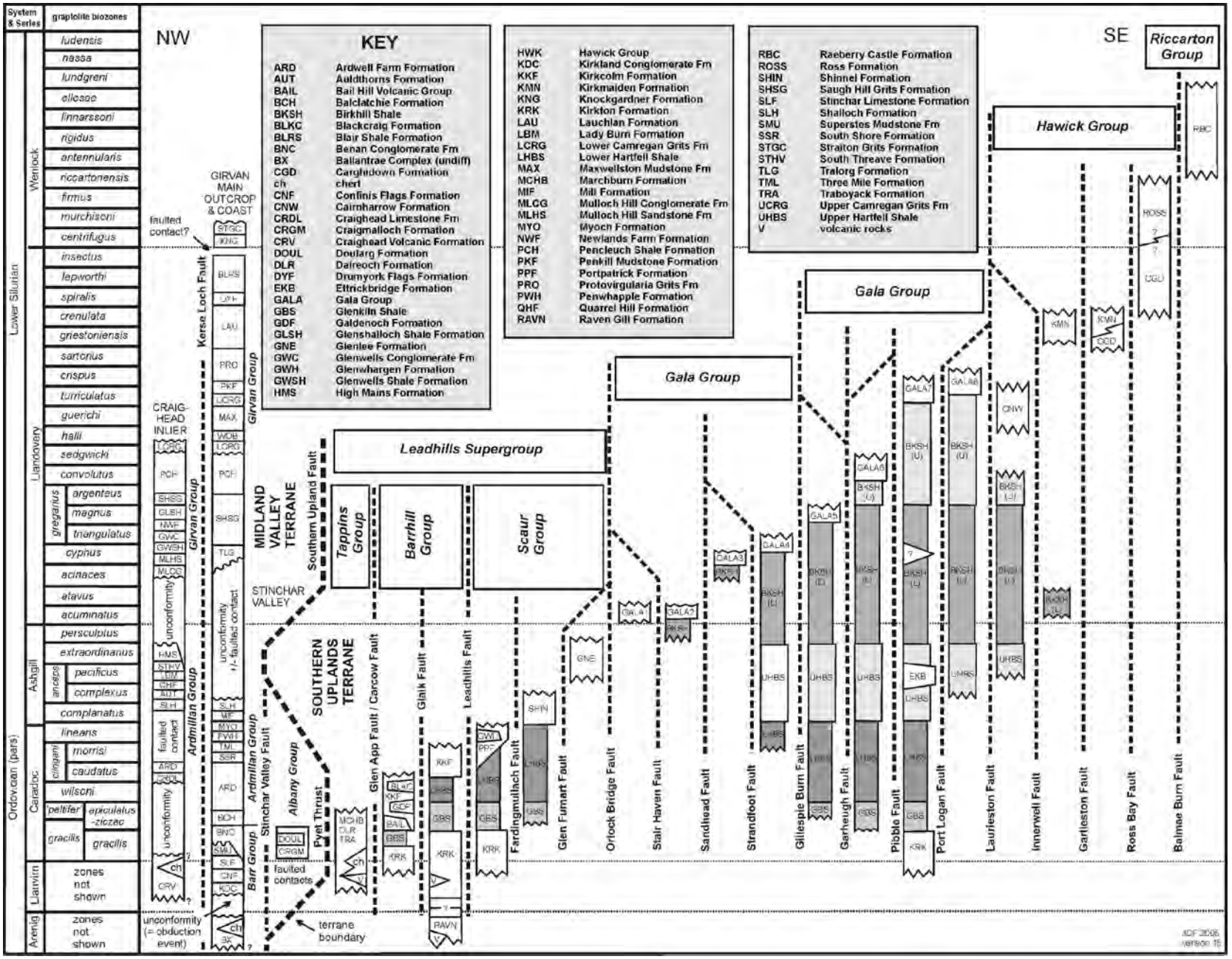

Figure 3. Tectonostratigraphical and chronostratigraphical diagram of the fault-bounded tracts of Lower Palaeozoic rocks within the Southern Uplands and the adjacent Girvan-Ballantrae area. In general, biostratigraphical correlation between tracts is only possible at the level of the Moffat Shales.

incorporated into the younger Kirkton Formation by a combination of sedimentary and/or tectonic means (Floyd 2001). The new collecting has demonstrated that conodonts are surprisingly common in the Kirkton Formation, with many fine examples obtained from numerous localities (Armstrong *et al.* 2002). The cherts have also yielded some remarkable examples of siliceous faunas including radiolaria and sponges which have been dissolved out of the rock using HF (Danelian & Floyd 2001). Although these taxa have the potential for worldwide correlation in the Lower Palaeozoic, their true value must await the development of a sufficiently rigorous biostratigraphy.

It is interesting that the 10Ma gap in the chert succession at Ravengill coincides almost entirely with the obduction of the Ballantrae ophiolite and associated parts of the complex along the southern margin of the now-adjacent Midland Valley Terrane (Ingham 2000).

In the overlying Moffat Shales, one of the long-outstanding problems was the poor resolution of the graptolite biostratigraphy in the *gracilis*, '*peltifer*' and *wilsoni* biozones, which were out of step with the Welsh and American zonation. This has been largely resolved by a massive study of the BGS collections from all the known localities, which has brought the Scottish zonation into line with successions elsewhere. As a spin-off, this work also demonstrated that most of the Southern Uplands localities actually represent the younger *apiculatus-ziczac* Biozone rather than the *gracilis* Biozone *sensu stricto* (Williams *et al.* 2004). At the same time, much progress has been made in the formal definition and type sections for many lithostratigraphical units, such as the Moffat Shale Group (Floyd 2001).

A notable feature of the Moffat Shales, particularly at Dob's Linn, is the presence of numeous white bentonite bands, thought to represent volcanic ash falls. Zircons from these have been used to provide an absolute radiometric time scale for the graptolite zones (Tucker *et al.* 1990).

Much of the overlying greywacke succession has been re-examined in great detail and the petrography, lithostratigraphy, geochemical and geophysical properties of the various formations extensively researched and published (see Floyd 2001 for a review).

Sedimentology

Modern analogues for the deposition of the greywacke succession can be seen in the fans of the Faroe-Shetland Channel. Here, gullies have been cut in the continental shelf and material transported downslope onto submarine fans. This, on a much larger scale, is envisaged as the mechanism for the transport and deposition of the sediment forming the greywackes of the Southern Uplands. Slumping has also been imaged, giving an idea of the potential sedimentary disruption in such environments and the difficulty of recognising it in the fossil record.

Good field evidence has emerged for the suspected interfingering and overlapping of fans from different sources (Floyd 1999) which can be demonstrated on both outcrop (bed-by-bed) and sub-terrane-scales. However, the typical exposure in many parts of the Southern Uplands is the parallel-sided succession of thin- to medium-bedded sandstones and laminated siltstones. In some successions, unusual units such as red mudstones occur, which may have the potential to be marker bands.

Rarer lithologies include the massive grits and conglomerates such as those at Glen Afton and Corsewall Point. These have clasts up to 1.3m long which have clearly not been transported for any great distance from their source, and probably represent channel-fill units near the top of a fan. Granite boulders from these conglomerates have been dated with clusters of ages at 490, 700 and 1230 Ma (Elders 1987)

All the classic sedimentary features of turbidite deposition are present, such as graded bedding, flutes, grooves and flame structures. Rippled tops to beds are also common in some areas. All these are also vital indicators of 'way-up'. Current directions can be derived from orientation measurements though these have to be assessed with caution due to the relatively small number of data and the uncertainties inherent in correcting for the steep dips and folding.

Structure and deformation

The structural understanding of the terrane has evolved in parallel with the sedimentological and stratigraphical advances. The long-recognised 'Southern Uplands Paradox' of northward younging successions managing to young southwards overall is elegantly explained by the accretionary prism model involving fault-bounded slabs of sedimentary rock successively accreted northwards by underthrusting previously accreted slabs. This is envisaged as driven by the northwards subduction of the Iapetus oceanic floor acting as a sort of 'conveyor belt' for the overlying fan deposits.

There is evidence for the relatively simple orthogonal closure of Iapetus during the mid- to late-Ordovician phase beginning to incorporate an element of sinistral shear from the mid-Llandovery onwards. This is seen in the general temporal merging of the formerly discrete deformation events of the Northern Belt, with clearly distinguished fold phases, into transpressional features such as curvilinear fold hinges seen in the younger Gala and Hawick rocks (Barnes *et al.* 1989).

Heavy minerals

One of the most potentially useful sedimentary provenance indicators is the detailed study of heavy minerals. These can provide a remarkable insight into the nature of the source rocks and how the provenance changed over time. Age dating of minerals such as zircon (Phillips *et al,* 2003) can also help to establish the age pattern of igneous activity, though possible inheritance aspects need to be considered. Many heavy minerals are of course very resistant to destruction and can persist through multiple sedimentary, metamorphic and even igneous cycles. However, detailed examination can usually resolve at least some of the history of individual grains and hence populations. As might be expected, the heavy minerals can provide useful confirmation and added insight into observed petrographic variation and can also suggest subtle or cryptic changes over time which may not be immediately obvious in the gross petrography (Mange *et al.* in press).

Geochemistry

Similarly, geochemical research into the lithogeochemistry of the formations provides valuable numerical evidence to confirm gross lithostratigraphical variation and perhaps pinpoint less obvious trends through time. The slightly second-hand approach of stream sediment analysis (G-BASE) has proved to be very effective in the Southern Uplands, probably because the lithogeo-

chemical variation is on a grand scale and consistent in relation to the sample density, and also because there has been surprisingly little smearing due to glaciation. This has confirmed the general trend in maturity of the source area(s) from granodioritic (and even ultrabasic) in the older Ordovician and Gala Group rocks to more granitic in the youngest Hawick and Riccarton groups. Of particular interest is the anomalously high Cr concentration in the northern part of the Gala Group (Figure 2 and Stone *et al.* 1999), which has been instrumental in confirming lithostratigraphical relationships in an area where the normal petrographical and biostratigraphical distinctions are unsatisfactory.

Conclusions

The accretionary prism model has become more accepted over time as evidence has accumulated from various new strands of research. Current BGS work in the Southern Uplands is concentrated in the eastern half, where there is evidence of new sedimentary units, not represented further west, being introduced into the succession. This situation has long been anticipated but has been difficult to prove in the absence of modern mapping. Such a scenario is entirely consistent with an element of strike-slip assembly of the terrane, evidence for which, though not always its scale, has been acknowledged for many years.

Acknowledgements

This paper is published by permission of the Executive Director, British Geological Survey, Natural Environment Research Council (NERC).

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Book review

Soil Erosion and Conservation by R.P.C Morgan, 2005, Blackwell Publishing, 304pp, (paperback) £29.95, ISBN 1 4051 1781 8

Morgan is Emeritus Professor of Soil Erosion Control at Cranfield University. He has over 30 years research experience in soil erosion from a variety of interesting places around the world, so this book has an excellent pedigree.

This book is a reprint of previous successful versions. As a geography teacher I think it is an ideal resource for undergraduate specialists or very bright A' level geography students. It is clearly set out in sections that puts soil erosion in the global context, going on to discuss the processes and mechanics of; and factors influencing soil erosion; it fully explains current models used in measuring and predicting soil erosion such as the Universal Soil Loss Equation (USLE). It also has a very good table of Manning's n values for estimating the friction coefficient, so if you are into models this a book for you. There are excellent sections on strategies for erosion control, including crop and vegetation management and soil management. Examples are drawn from Europe and USA. I would refer to this book at University level 1 as part of an Integrated Catchment Management module (after all I am interested in rivers…) – but I have to be honest and wonder how it fits in with current OU courses.

Penny Widdison, PhD, OU Tutor

Tracking Dinosaurs in Scotland

Neil D L Clark, Hunterian Museum, University of Glasgow, Glasgow, G12 8QQ

Abstract

Dinosaurs, the Loch Ness Monster not included, are a rarity in Scotland. Although dinosaurs have been known of in England and elsewhere in the world for over 300 years, it was only in the last 23 years that dinosaurs began to appear in Scotland. The first discovery of dinosaur remains on the Isle of Skye was that of a single 49cm long ornithopod footprint discovered in 1982. Since then dinosaur footprints and trackways have turned up in Bathonian rocks of the Middle Jurassic Valtos Sandstone, Duntulm and the Kilmaluag Formations. Dinosaur bones have also been found in rocks of Hettangian, Bajocian and Bathonian age.

A story of broken limbs, helicopters and restricted access due to dangerous rockfalls, dinosaur hunting and tracking is still a dangerous sport in Scotland, not to be undertaken by the faint hearted. The Isle of Skye can be regarded as one of the foremost Middle Jurassic sites for dinosaur remains worldwide and continues to reveal its world-record-breaking secrets more and more, every year.

Introduction

Dinosaur fossils of any kind are rare in Scotland. Apart from a dubious record of a single track of a small saurischian dinosaur from Caithness (Sarjeant 1974), and *Saltopus elginensis*, a possible dinosaur, or dinosaur precursor, from the Triassic rocks of Morayshire (Benton 1997), only sediments on the foreshore around the coast of the Trotternish Peninsula, Isle of Skye have produced numerous bones and footprints of dinosaurs (Figure 1).

The first evidence of a true dinosaur to be found in Scotland was a large footprint discovered on a loose block of muddy limestone from the Lonfearn Member of the Lealt Shale Formation at Rubha nam Brathairean in 1982. This footprint, although originally interpreted as having been produced by a theropod dinosaur, is now thought to belong to an ornithopod (Andrews & Hudson 1984; Delair & Sarjeant 1985). Since then, dinosaur footprints and trackways have been found in the Valtos Sandstone Formation (Bathonian) near Staffin at Dun Dearg and Kilt Rock (Clark & Barco Rodriguez 1998; Clark 2001a), the Duntulm Formation (Bathonian) near Staffin at An Corran (Clark *et al.* 2004), and the Kilmaluag Formation at Score Bay (Clark *et al.* 2005) (Figure 2).

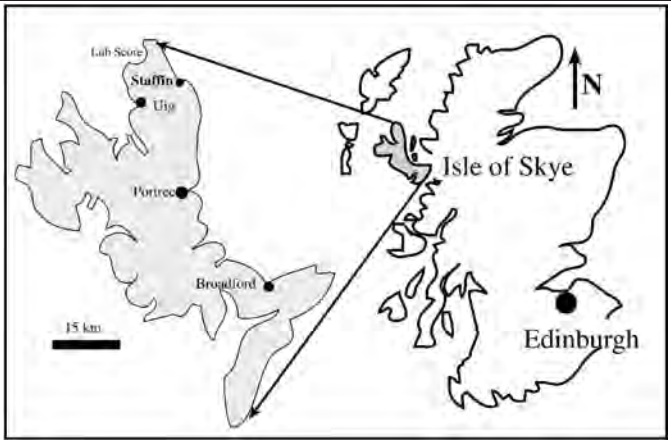

Figure 1. Map of Scotland and Skye

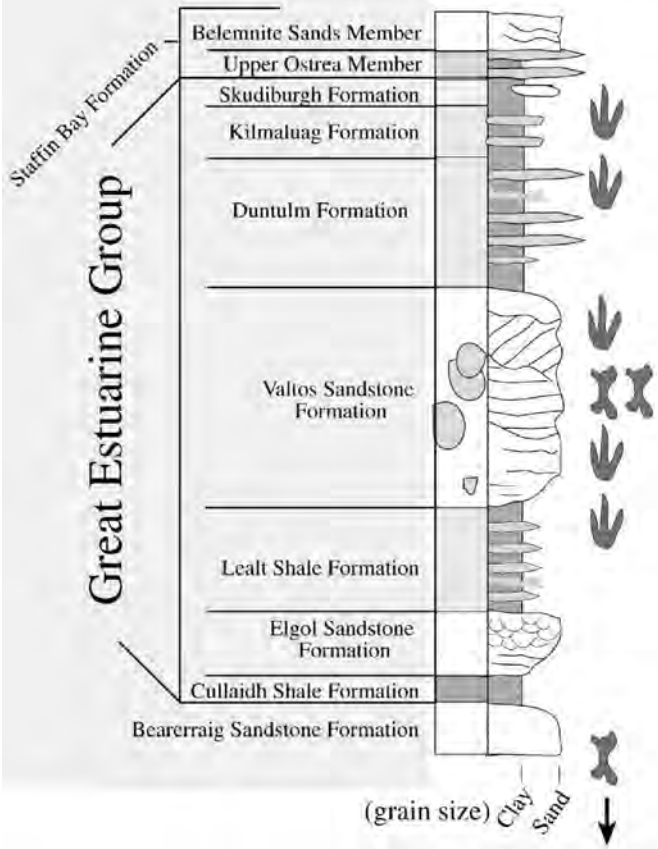

Figure 2. Stratigraphy of the Middle Jurassic Great Estuarine Group on the Isle of Skye showing the distribution of dinosaur footprints and bones.

Dinosaur bones are also known from Scotland. A theropod tibia was found in the Broadford Beds Formation (Hettangian) in the Strathaird Peninsula, southern Isle of Skye (Benton *et al.* 1995), a thyreophoran ulna and radius came from the Bearreraig Sandstone Formation (Bajocian) at Bearreraig Bay, northern Isle of Skye (Clark 2001b), and cetiosaur bones and a coelophysid-like tail bone were discovered in the Valtos Sandstone Formation at Dun Dearg near Staffin (Clark *et al*. 1995, Clark *et al.* 2004, Liston 2004).

Loch Ness Monster

Most people now believe that the Loch Ness Monster is not a dinosaur although there are still a few who cling to the idea of it being a plesiosaur. What it is, exactly, remains controversial, but it is unlikely to be a resident air breathing giant marine reptile or there would be a substantially greater number of sightings. Saint Adomnàn related the first report of the monster in the 7th century (Sharpe 1995) as he told of the story of Saint Columba's travels and miracles. In about the year 565, Saint Columba sent the monster fleeing by commanding it to leave in God's name thus saving a man the monster was about to attack. Saint Adomnàn wrote this over 100 years after the event and, I believe, may have had his stories mixed. In the chapter previous to the encounter with the monster of Loch Ness, Saint Adomnàn mentions the travels of Saint Columba on the Isle of Skye. Perhaps what Saint

Columba was banishing to the sea was a Jurassic plesiosaur, or ichthyosaur dug up in Skye? This is pure conjecture and does not explain the many sightings since 1933 when the A82 trunk road was completed along the west of Loch Ness.

So, what is *Nessiteras rhombopteryx,* the Loch Ness Monster (Anon 1975, Scott & Rines 1975)? Well, as Nicholas Fairbairn pointed out, the pseudo-scientific name for it is an anagram of "Monster hoax by Sir Peter S.". Scott's name for the monster is pseudo-scientific because it does not follow the rules of the code for zoological nomenclature for naming new animals. We cannot be certain that all the sightings are of the same phenomenon, nor do we have any physical remains in any national repository with which to compare this phenomenon with any other. All we have are eyewitness accounts, fuzzy photographs, distant video footage and a host of proven hoaxes.

Many of the sightings have been explained as floating logs or freak waves, but there are still quite a number of unexplained sightings. Another possible explanation for some of the early sightings that may be explored further concerns travelling circuses. Circus fairs visiting Inverness would have stopped on the banks of Loch Ness to allow their animals to rest. If the elephants were allowed to swim in the loch, only the trunk and two humps would be seen: the first hump being the top of the head and the second being the back of the animal. The resulting impression would be of an animal with a long neck and two humps – more if there were more than one elephant in the water. It is not surprising that the circus owner Bertram Mills offered a £20,000 reward to anyone who could capture the monster for his circus, because it was likely that he already had one in his circus – perhaps the Loch Ness Monster itself! It is therefore not surprising that no one has yet claimed the reward!

Figure 3. Interpretation of a swimming elephant with a darker Loch Ness Monster profile above the water line.

The Early Days

The first footprint to be found was discovered by Julian Andrews and subsequently collected for the collections of the Hunterian Museum in Glasgow by Stan Wood. At the time is was unclear whether the footprint was that of a theropod or an ornithopod (Andrews & Hudson 1984), but due to the spatulate shape of the toes it was finally considered to be the footprint of an ornithopod. The large size of the tridactyl footprint (49cm in length) suggests that it was likely to have been of a large facultatively bipedal ornithopod similar to *Iguanodon* (Delair & Sarjeant 1985). The only dinosaur fitting this description of a similar age is *Camptosaurus* from the Upper Jurassic of North America.

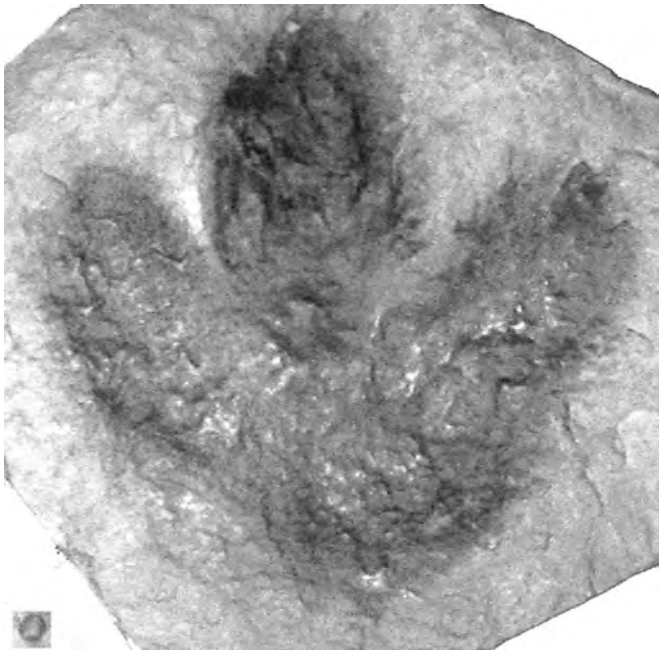

Figure 4. The Lealt Shale Formation footprint showing rounded toe impressions (X0.15).

Since the discovery of the first dinosaur track in 1982 in the Lonfearn Member of the Lealt Shale Formation (Bathonian, Middle Jurassic), it was not until about ten years later that the next discovery was made. A Mr Lachlan Scott-Moncrieff of Staffin gave a small fragment of an unidentifiable dinosaur bone to Mr Dugald Ross of the Staffin Museum, Isle of Skye. It was not identified as being part of a dinosaur bone until 2001 when it was first shown to me. This bone appears to have been found before other discoveries reported in the press in 1995 and before 1992.

Two dinosaur bones were reported in 1995 that come from opposing ends of the Isle of Skye. A small bone in the collections of the National Museums of Scotland, Edinburgh, was found in 1992 by a German collector (Matthias Metz) in rocks of the Upper Broadford Beds (Sinemurian, early Jurassic) from southern Strath and is likely to be the tibia of a ceratosaurian dinosaur similar to *Coelophysis* or *Dilophosaurus* (Lower Jurassic North American dinosaurs). This bone is approximately 127mm long (Benton *et al*. 1995). The other reported bone (Clark *et al*. 1995) has a reconstructed length of about 900mm and is thought to be a limb bone of the sauropod *Cetiosaurus* (a Middle Jurassic European and North African dinosaur).

Dougie the Dinosaur

The sauropod bone is from rocks of the Valtos Sandstone Formation (Bathonian, Middle Jurassic) of the Trotternish Peninsula in the northern part of the Isle of Skye. An unknown collector, who returned it anonymously to be reunited with the rest of the bone, had removed the mid-shaft. Chris Mitchell and Jan Wolfe of Staffin (now of Seil Island) found and collected the distal end separately. The proximal end was found by Drs Doug Boyd and John Dixon of BP Exploration and reported to Dugald Ross of the Staffin Museum. The dinosaur became affectionately known as 'Dougie the Dinosaur', being named after both Dugald Ross and Doug Boyd. The limb bone can now be seen in the collections of the Staffin Museum (Clark *et al.* 1995; Liston 2004). There is some dispute as to which limb the bone belongs.

Figure 5. Impression of the reconstructed cetiosaur 'Dougie the Dinosaur'.

Figure 7. Cetiosaur tail bone from north of Kilt Rock near Staffin, found by Dugald Ross and David Morgan.

Originally thought to be either a tibia or femur, it is now considered more likely to be a bone of an anterior limb (Liston 2004).

More tracks, a big break and more bones

In January 1996, a series of footprints of small dinosaurs was discovered in rocks of the Valtos Sandstone Formation. One footprint type was probably produced by a small ornithopod and the other was probably that of a small theropod. Whilst attempting to collect the footprints, I suffered an injury that nearly cost me my right leg. I broke my leg, presumably as a result of a stress fracture resulting from the use of power tools, and was airlifted to Stornoway, Isle of Lewis. As the leg was not secured properly the airflow from the helicopter rotaries caused the lower part of the leg to flap wildly inducing greater damage. The other members of the team were left to recover the broken blocks containing the dinosaur footprints that are now in the collections of the Hunterian Museum (Clark 2001a).

Also in 1996, another caudal vertebra was found. This one was much larger than the previous one and was found by David Morgan and Dugald Ross near Staffin. Although reported in the press as being from the tail of a large theropod, it is actually from the tail of a sauropod akin to *Cetiosaurus*. Several other bones have been found from the same formation (Valtos Sandstone Formation) although most of these are unidentifiable except in the broadest possible terms such as 'dinosaur ribs' and '?dinosaur bones' (Clark *et al*. 2004).

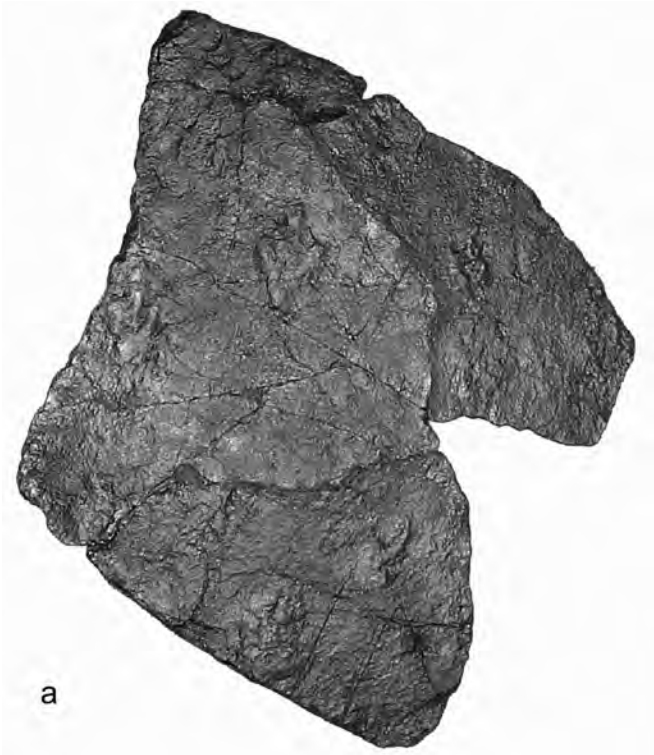

Figure 6. a, Dinosaur footprints from the winter 1996 discovery at Rubha nam Brathairean (X0.05); b, X-ray of my leg after it was put back together (X0.25).

In situ at An Corran

The discovery in early 2002 of a footprint on the foreshore at An Corran by Cathie Booth whilst walking her dog, near the Staffin slipway led Dugald Ross, Paul Booth and myself to the first *in situ* dinosaur remains from Scotland. These footprints, numbering over 15, contain some of the largest footprints yet found on Skye at over 530mm in length. The footprints are from the Duntulm Formation (Bathonian, Middle Jurassic) (Clark *et al.* 2004) and are easily accessible at low tide during the winter months. During the summer months, however, the footprints are usually covered by a thick layer of shifting sands (Clark 2003).

Figure 8. Large *in situ* theropod dinosaur footprints at An Corran.

World Breakers

The earliest thyreophoran and the tiniest dinosaur footprint

In 1997, Colin Aitken of Edinburgh found another set of bones. These were found in rocks from the Bearreraig Sandstone Formation (Early Bajocian, Middle Jurassic) and were a partial ulna and a partial radius of a thyreophoran dinosaur related to either stegosaurs or ankylosaurs. In a similar manner to the first sauropod limb bone, the bone found by Mr Aitken was subsequently collected by an unknown visitor. This unknown person broke the rock containing the bone and removed leaving a pile of rubble and removing the bone (probably the humerus). Dugald Ross collected the rubble and found it to contain the ulna and radius bones of the thyreophoran dinosaur. At least some of the bones of what may be the earliest ankylosaur remains have been rescued for science from obscurity into the collections of the Staffin Museum (Clark 2001b). It would be a bonus if the missing bone, possibly the humerus, were to be reunited with the ulna and radius of such an important dinosaur.

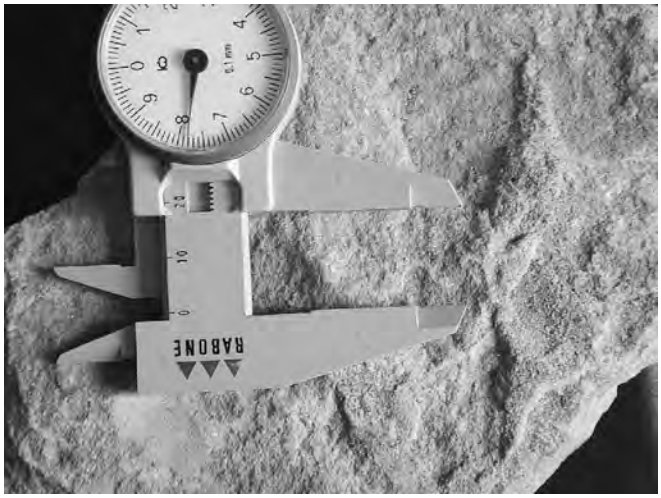

Figure 9. The World's smallest dinosaur footprint from Lub Score (X0.65).

In late 2002, dinosaur footprints were discovered on loose blocks of sandstone, as well as *in situ,* on the foreshore at Lub Score, northwest Trotternish Peninsula, Isle of Skye. The majority of these footprints were much smaller than any previously found in Scotland at about 7-8cm long, and were closely associated with larger footprints of what seems likely to be the same species of about 25cm long. These footprints are stratigraphically younger than any other dinosaur remains found in Scotland to date. Some of these footprints represent the trackways of young theropod dinosaurs sometimes associated with those of an adult. It has been postulated that these may represent the first ever evidence of a theropod family group. The World's smallest dinosaur footprints, measuring 1.8cm long were also found from these rocks (Clark *et al.* 2005) and will be featured in this year's Guinness Book of World Records.

The youngest coelophysid

Also in 1995, a small tailbone found in the vicinity of the sauropod bone was found. It turns out that this bone is probably from the tail of another small ceratosaurian dinosaur similar to *Coelophysis* (a Lower Jurassic North American dinosaur). This bone can be seen in the collections of the Hunterian Museum (Clark *et al.* 2004; 2005).

Figure 10. Coelophysid-like tail bone from the Valtos Sandstone Formation (X2).

In Memory of Millie

Millie the Dinosaur was not a real dinosaur, although she became real to a great number of dinosaur enthusiasts in Scotland, and was dismantled in the grounds of the University of Glasgow on Saturday 21st May 2005. The reconstructed rendition of a *Tyrannosaurus rex* was popular with visitors, students, and palaeontologists from around the World, but the university could not afford to keep repairing the imposing artwork that was costing in excess of £2,000 a year. Millie was a sculpture of great value both as a work of art and as a scientific representation based on current knowledge of a dinosaur.

During the week prior to being demolished, about 720 students past and present from the University of Glasgow, as well as admirers from all over the World, pledged their support by signing an online petition set up by an anonymous group of concerned students, after hearing a rumour that the University was planning to move Millie.

Millie was originally installed in 2001 as part of the BBC's Walking With Dinosaurs exhibition, held in the Hunterian Museum. Millie, the largest replica *Tyrannosaurus rex* in the World, was only meant to stay for three months to promote the

a

b

Figure 11. a, Millie the *Tyrannosaurus rex* at the University of Glasgow; b, Millie partly complete.

exhibition, but lasted for over 3 years. As one of the last of the Scottish dinosaurs, and probably one of the most popular, it is sad to reflect on her extinction.

What the future holds

The Isle of Skye continues to bear dinosaurian fruits. On average, about one discovery is made each year, and nearly every discovery is of something different and new to Scotland. This means, at the current rate, that it will take over 200 years to collect a complete dinosaur. There is still much to be discovered and learned from dinosaurs on the Isle of Skye. My hope is that material that has disappeared from Scotland's Dinosaur Isle will eventually be made available for research, and that collecting on behalf of the Scottish museums continues to reap rewards, as it has done over the last 10 years.

One interesting aspect of the research into the dinosaurs from Scotland is that the dinosaurs have more in common with North American dinosaurs at that time than with Europe and Africa. This is not the whole story as there are also similarities with Middle Jurassic remains from elsewhere in the UK and Europe (Clark *et al.* 2004, 2005). Perhaps Scotland represented a refugium for Lower Jurassic North American dinosaurs such as *Coelophysis*? Not having any body fossils from the Middle Jurassic of North America makes it difficult to draw too many conclusions as yet, but more discoveries are being made each year in North America and it may just be a matter of time before they find their first Middle Jurassic dinosaur bones.

Acknowledgements

Tooth and Claw model makers Joe Cherrie, John Riddell and Kate Nelson for producing Millie the Dinosaur. Jeff Liston for the Millie concept. Thanks to all those who have contributed to the discovery of dinosaurs in Scotland from Research Scientists to Winklers. Thanks also are especially due to Dugie Ross, Paul and Cathie Booth, Chris Mitchell, Jan Wolfe, David Morgan, Colin Aitken, Colin MacFadyen, Stephen Varwell, Jim Rennie and all the anonymous collectors, researchers and facilitators from around the World. Clare Clark is thanked for pointing out the possibility of the Loch Ness Monster circus connection.

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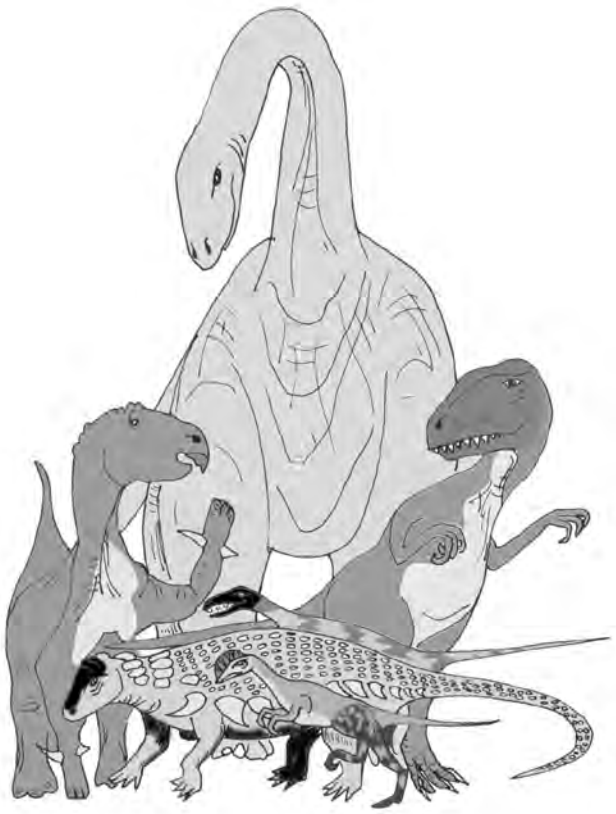

Figure 12. A selection of dinosaur types represented on the Isle of Skye (approximately X0.015).

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Book reviews

Fossil Plants by Paul Kenrick & Paul Davis, 2004, Natural History Museum, London, 216pp, £16.95 (paperback) ISBN 056509176X.

Most books about fossil plants adopt a taxonomic approach to their subject, identifying and illustrating the key features of the major groups, or the components of particular palaeoflora. This book is not one of these. Instead the authors explore the broad themes in the evolution of plants and the impact of plants on the Earth's environments. The evolution of the different groups, including organs, reproductive strategies and broad taxonomic relationships, are used to support this approach. The result is a very informative and readable book which will be of interest to anyone with an interest in the history of life. OU students taking courses such as Evolution (S365) and Earth and Life (S269) will find this book to be a valuable supplement to their studies.

Fossil Plants begins by exploring the origin of the Eukarya, including the green algae, in the Proterozoic. The fossil evidence includes stromatolites and microfossils. The environmental impact lay in the appearance of photosynthesis, which began to release free oxygen into the atmosphere. Most of the action in the fossil record, however, comes in the Phanaerozoic, and most of the book is about the impact of land plants. The chapter on the "Devonian Explosion", which saw the astonishing evolution of land plants from small forms of the early Devonian to complex forest ecosystems, is excellent. The evolution and environmental impact of roots, leaves, seeds and trunks are clearly explained. Other major themes include the Carboniferous coal swamps, the origin and environmental impact of the angiosperms, and the changing ecological relationships between animals and plants.

For those familiar with the standard divisions of geological time, the history of plants provides a somewhat different perspective. The major stages in the history of plant life on land can be divided into the Palaeophytic (Silurian to early Permian), Mesophytic (mid-Permian to early Cretaceous) and Cenophytic (mid-Cretaceous to the present). Plants were less affected than animals by the major mass extinctions that mark the boundaries between eras and periods. Thus the Palaeophytic floras dominated by ferns, clubmosses and seed ferns (cordaites) began to give way to the Mesophytic floras dominated by conifers, ginkgos and cycad-like forms, during the Permian. The Cenophytic floras, dominated above all by the angiosperms, began to supplant the Mesophytic floras during the mid-Cretaceous, and the KT extinction hardly phased them.

David Scarboro OU Tutor

The Geology of Australia, David Johnson, 2004, Cambridge University Press, 276 pp, £27.99 (paperback), ISBN 0521841216 (hardback), 0521601002 (paperback).

From the OU courses I've done, Australia means very ancient rocks, BIFs, Ediacaran fauna, the break-up of Gondwana, present day stromatolites. At Stirling I learnt that inter-cratonic orogenies in Australia might provide analogies for Scotland without having to postulate terrane accretion. All this and a great deal more is in Johnson's book, which is intended as "a new summary of Australian geology", there not having been such a work for 50 years or so. As such it looks extremely successful, and is aimed at those with little or no understanding of geology. Chapter 2, over 40 pages, is "a geology primer", the points made being of course illustrated by Australian examples; the last two chapters also deal with general matters. I am sure it would fill the mission intended for comparative beginners; the text is always clearly expressed, and it is extremely attractively produced, with a generous number of colour photographs and most figures being in colour.

I thought it more clearly set out than Jocelyn Thornton's New Zealand Geology; that tries to do too much, being a "geology primer" arranged as a chronological field guide, with all figures and maps in black and white, and with the tectonic events not explained nearly as clearly as Johnson does. He has not written a field guide, although his book would be good to have at hand (and not too heavy) when visiting any geologically significant area. Having currently an interest in New Zealand geology, I was surprised that Johnson's interest in fragments of Gondwana stops to the east with the Lord Howe Ridge; there is not a single mention of the land mass beyond and its relation to Australia (a map where New Guinea is mis-labelled "New Zealand" did make me wonder if Johnson actually knew where New Zealand was!)

Another point on which I would have liked some information, or even speculation, is the eventual welding of the two large Gondwana terranes, Australia and India, into what is now one plate. I believe not much is known about this, but I would have liked some acknowledgement of that!

These are small points when set against the wealth of clear and succinct information about the geology underlying all the physical features of Australia. There are full bibliographies for the more advanced reader at the end of each chapter. A very good buy.

Philip Clark, BSc (Hons) Open, MA Oxon.

The Caledonian architecture of East Greenland 72°–75°N

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Introduction

The Geological Survey of Denmark and Greenland has completed regional 1:500 000 mapping of the entire 1300 km length of the East Greenland Caledonides (Figure 1). As a guest in parts of this enterprise, I have been privileged to explore large tracts of this exciting terrain with my co-author (AKH) and others. This article outlines a brief personal perspective of the southern part of the orogen, gained from the results and ongoing collaboration following my fieldwork in the East Greenland Caledonides between 1995 and 1999. A 1:500 000 map of the Kong Oscar Fjord region, 72°–75°N (Escher 2001) and a special map of the entire orogen at 1:1 million (Henriksen 2003) have both recently been published.

The East Greenland Caledonides is broadly divisible into a western marginal (thin-skinned) thrust belt and an eastern thick-skinned thrust belt (Figure 1). The major lithotectonic divisions established in the southern half of the orogen for the Kong Oscar Fjord region (72°–75°N, Figure 2) document regional large-scale Caledonian thrusting (Higgins & Leslie 2000; Higgins *et al.* 2001). These divisions include parautochthonous foreland overridden by two major thrust sheet assemblages (the Niggli Spids and Hagar Bjerg Thrust Sheets), and the uppermost Franz Joseph allochthon, (Figures 2 & 4). Higgins *et al.* (2004) delineate the salient features of the newly established lithotectonic divisions, summarise isotopic dating of key events in the geological evolution of the region, and outline a reconstruction of the Laurentian margin prior to, and during, Caledonian orogenesis.

Kong Oscar Fjord Region tectonic architecture

Parautochthonous foreland

Foreland rock units crop out within tectonic windows (Figures. 1, 2 & 4) and in the westernmost nunataks. All units show Caledonian deformation, and are therefore interpreted as parautochthonous rather than strictly autochthonous foreland (Higgins *et al.* 2001).

The Eleonore Sø window extends at least 100km from north to south and 20km from east to west (Figures 2 & 4, Higgins *et al.* 2001). The Eleonore Sø complex dominates the geology of the window and comprises low-grade metamorphosed sandstones and mudstones, carbonate rocks and a volcanic sequence of tuffs and pillow lavas. Quartz porphyry bodies intruded into this foreland complex at *c.*1970Ma (SHRIMP U-Pb zircon age, F. Kalsbeek, unpublished data) prove a Palaeoproterozoic or older age.

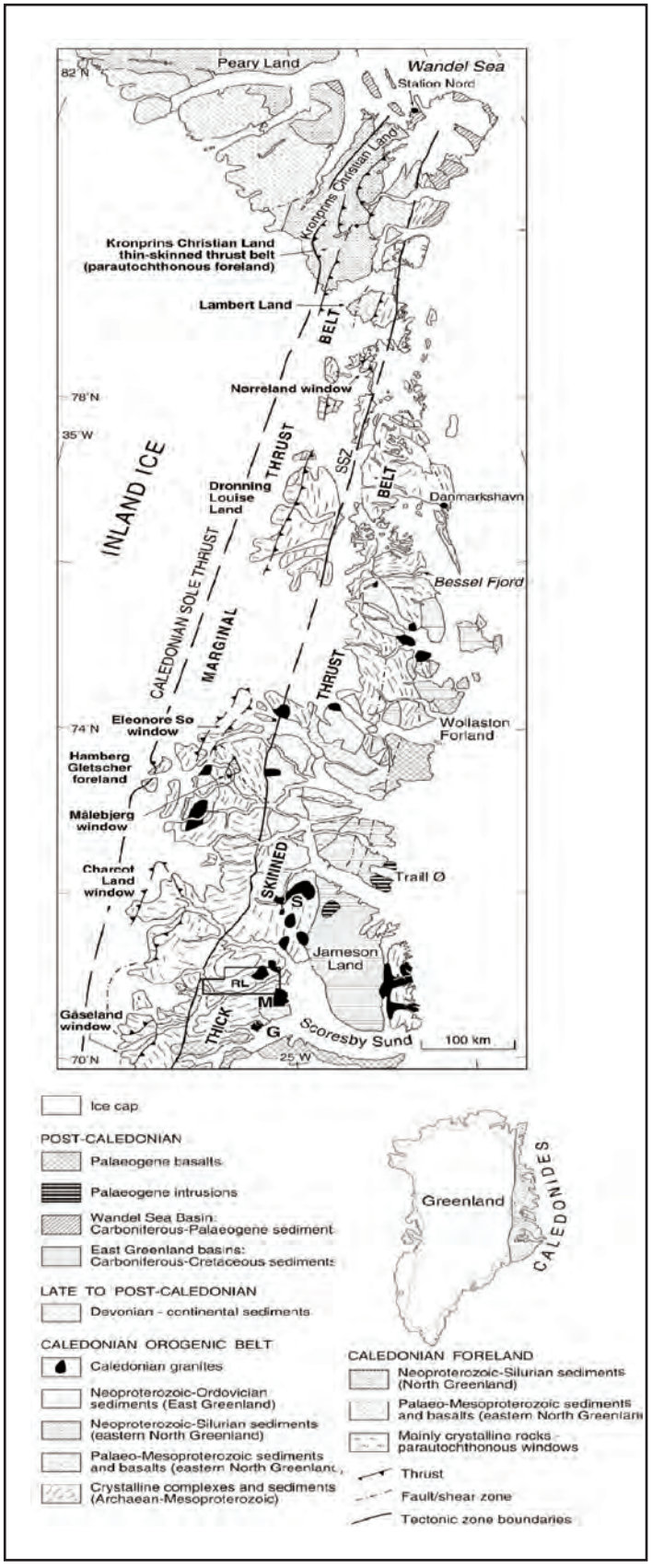

Figure 1. Geological map of the east Greenland Caledonides. The western limit of Caledonian deformation, the Caledonian Sole Thrust is largely concealed by the Inland Ice. The foreland windows occur within the western thin-skinned marginal thrust belt whereas the eastern thick-skinned thrust belt is partly obscured by post-Caledonian sediments and Palaeogene basalts. RL – Renland

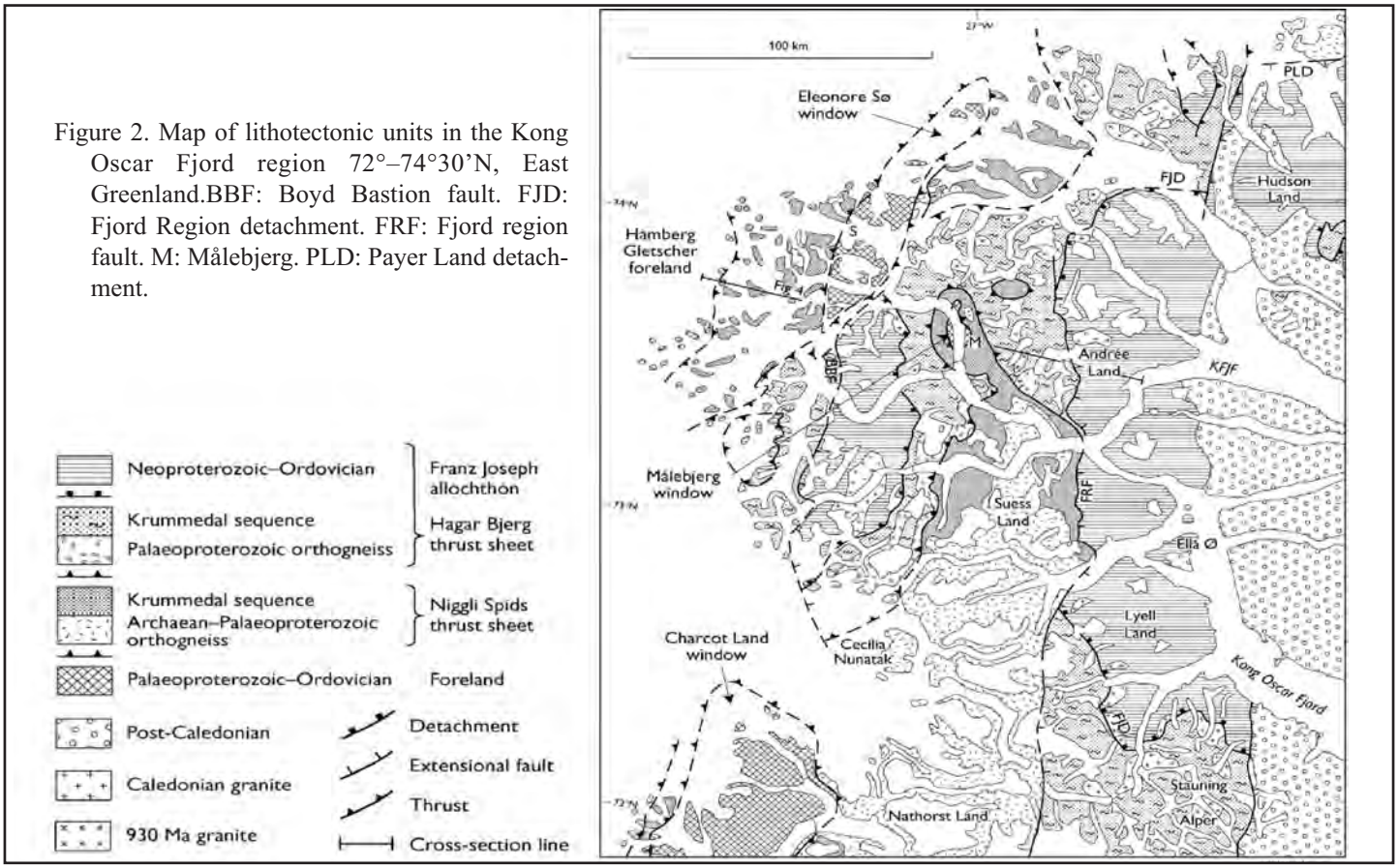

Figure 2. Map of lithotectonic units in the Kong Oscar Fjord region 72°–74°30'N, East Greenland.BBF: Boyd Bastion fault. FJD: Fjord Region detachment. FRF: Fjord region fault. M: Målebjerg. PLD: Payer Land detachment.

Early Cambrian Slottet Formation quartzite overlies the Eleonore Sø complex with profound unconformity (Figure 3). The uppermost part of the formation preserves abundant well-preserved *Skolithos* tubes (up to 80cm long), indicating a maximum early Cambrian (Tommotian) age for that part of the succession. The Slottet Formation quartzite is overlain by a carbonate sequence, the Cambrian–Ordovician Målebjerg Formation (Smith *et al*. 2004).

The Målebjerg window (Figures 2 & 4) is situated about 35km east of the Eleonore Sø window. The window exposes gneisses, unconformably overlain by Slottet Formation quartzite which preserves variably sheared examples of Skolithos. A 31m thick clastic sequence containing two diamictite beds is locally preserved below the Slottet Formation, and is correlated by Smith *et al.* (2004) with the diamictites of the Vendian Tillite Group (Hambrey & Spencer 1987). As in the Eleonore Sø window, the Slottet Formation is overlain by Målebjerg Formation carbonates.

Figure 3. West-dipping white and rusty brown quartzites (~350m thick) of the Slottet Formation rest with marked unconformity on dark-coloured clastic sediments of the Eleonore Sø complex at Slottet in the Eleonore Sø window, looking northwards. The summit of Slottet (1933m high) is 600m above the glacier surface.

These two anticlinal windows are representative of the foreland sequence over-ridden by Caledonian thrust-stacking (Higgins *et al.* 2001). The contrast between the thin foreland Neoproterozoic–Lower Palaeozoic succession (220–400m) in the windows and the apparently very thick (18.5km) correlative succession in the Franz Joseph allochthon is striking. Stacking thrust sheets in which these records are preserved demonstrate significant contraction across the orogen, and argue for the existence of a major sedimentary basin in this Laurentian sector of the Iapetus passive margin, that in the early Palaeozoic was perhaps 500-700km wide (Higgins & Leslie 2000).

Niggli Spids Thrust Sheet

The Niggli Spids Thrust Sheet structurally overlies the foreland windows (Figure 4), and comprises two main lithological units: Archaean (2800–2700Ma) to Palaeoproterozoic (*c.*1900Ma) crystalline gneiss complexes overlain by an earliest Neoproterozoic supracrustal sequence (Krummedal succession). The Krummedal succession largely comprises metamorphosed mudstone and sandstone (Higgins 1988); the contact with the gneiss complexes is generally strongly tectonised but locally is clearly an original unconformity, e.g. around Niggli Spids (Escher & Jones 1998). The upper boundary is the Hagar Bjerg Thrust.

The Niggli Spids Thrust Sheet is conspicuously lacking in widespread migmatisation and the occurrences of peraluminous granite that characterise the over-riding Hagar Bjerg Thrust Sheet. No Neoproterozoic deformation has been demonstrated within the thrust sheet but several Caledonian deformation phases associat-

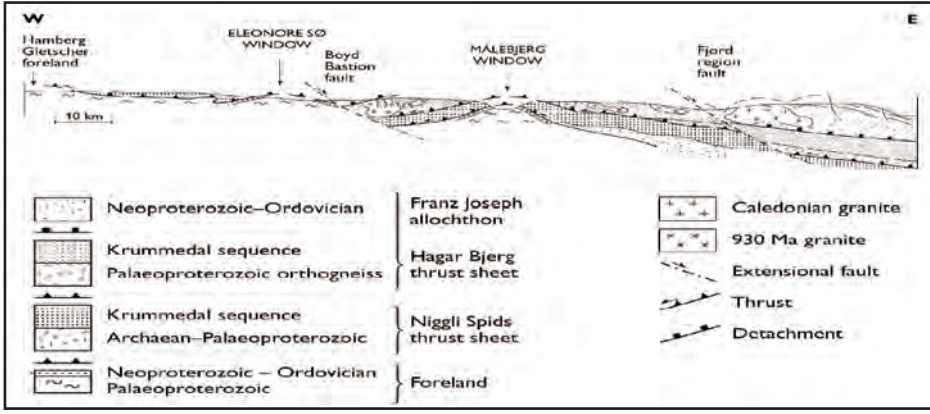

Figure 4. Cross-section through the Caledonian orogen in the Kong Oscar Fjord region, East Greenland, showing thrust sheet architecture after Higgins & Leslie (2000). The detachment at the base of the Franz Joseph allochthon is the Fjord Region detachment in the east in the hanging wall of the Fjord region fault and the Petermann detachment in the west in the hanging wall of the Boyd Bastion fault. See Figure 2 for section line.

ed with medium-to high-grade metamorphism are recognised. The gneiss complexes have suffered a variable degree of Caledonian reworking during westward transport.

A minimum displacement estimate for the Niggli Spids Thrust Sheet is indicated by representatives of the Niggli Spids Thrust Sheet about 90km west of the Målebjerg window (Figure 4).

Hagar Bjerg Thrust Sheet

The Hagar Bjerg Thrust sheet everywhere structurally overlies the Niggli Spids Thrust Sheet (Figure 4), and incorporates a major Palaeoproterozoic orthogneiss unit and a considerable thickness of high-grade Krummedal sequence metasandstone and metamudstone. Metasediments of the Hagar Bjerg Thrust Sheet are extensively migmatised, and host both early Neoproterozoic (*c.*940-910Ma) and Caledonian (*c.*435-425Ma) S-type granites produced by melting of the Krummedal metasediments that host them (Kalsbeek *et al.* 2000; Watt *et al.* 2000). Where the gneiss unit is missing, as in western Andrée Land, the thrust contact is easily traced as a marked feature between high-grade metasediments with abundant granites in the hangingwall against lower-grade metasediments lacking granites (Niggli Spids Thrust Sheet) in the footwall (Figure 5).

The older of the two generations of granites (thick sheets of leucogranite, often with large feldspar augen) has yielded SHRIMP protolith ages of 915–910Ma (Leslie & Nutman 2003). These augen granites postdate regional-scale tight to isoclinal folding and upper-amphibolite-facies metamorphism in the Krummedal sequence host rocks implying that orogenic deformation occurred between deposition of the Krummedal sequence and formation of the granites.

The pervasive fabric and metamorphic assemblages in both the gneisses, and the overlying Krummedal metasediments, are considered to be dominantly of Caledonian age. Caledonian high-grade metamorphism of Krummedal metasediments (Jones & Escher 2001; Watt *et al.* 2000) locally reached granulite facies (dated at *c.*430Ma in Renland, Leslie & Nutman 2003). Anatexis led to growth of rare partial rims of 430Ma metamorphic zircon on detrital zircon grains in the Krummedal sequence (Kalsbeek *et al.* 2000). Leucogranites of Caledonian age (435–425Ma) range from veins to major plutons and are the subject of an extensive literature, e.g. Kalsbeek *et al.* (2001), White *et al.* (2002).

In the absence of recognised cut-offs of key units, displacement of the Hagar Bjerg Thrust Sheet with respect to the underlying Niggli Spids Thrust Sheet cannot be tightly constrained. However, assuming a normal forward-propagating development, the Hagar Bjerg Thrust Sheet must have been derived from a region ESE of that occupied by the Niggli Spids Thrust Sheet. The westernmost outcrops of the Hagar Bjerg Thrust Sheet are at least 100km distant from the easternmost outcrops of the Niggli Spids Thrust Sheet (Figure 2), a minimum estimate of thrust displacement.

Figure 5. Contact between the Hagar Bjerg thrust sheet (HBTS) and the Niggli Spids thrust sheet (NSTS) in Andrée Land. Light-coloured rocks in the HBTS are abundant granite sheets and veins (~930Ma and ~425Ma) hosted by the Krummedal supracrustal sequence. The dark-coloured Krummedal sequence rocks of the NSTS lack granite veins and sheets. The contact between the thrust sheets is here a WNW-directed thrust, but a few kilometres to the south the contact is a more steeply inclined extensional fault. Highest summit is 1000m above the valley floor.

Figure 6. Eleonore Bay Supergroup succession on the northern cliffs of Geolog Fjord, northern Andrée Land. This succession makes up the lower part of the high-level Franz Joseph allochthon, the boundary with the Krummedal sequence rocks of the Hagar Bjerg Thrust Sheet occurs in the lower left part of the section in view. The cliffs are 1100 – 1200m high.

Franz Joseph allochthon

The structurally highest Caledonian allochthonous division in the Kong Oscar Fjord region comprises the very thick Neoproterozoic–Ordovician succession distinguished as the Franz Joseph allochthon. This succession is dominated by the Eleonore Bay Supergroup (Figure 6) whose lower contact is a shear zone, likely to be a modified unconformity, and distinguished as the Petermann Bjerg detachment in the west and the Franz Joseph detachment in the east (Figure 4). Metamorphic grade increases downwards towards the basal detachment; a number of Caledonian granite plutons occur in the lowest levels of the allochthon. The highest preserved Ordovician rocks in the allochthon contain conodonts with very low colour alteration indices (Stouge *et al.* 2002) which implies that the Franz Joseph allochthon was probably the highest structural element of the Caledonian thrust pile. The deformation pattern in the Franz Joseph allochthon probably developed largely during westwards Caledonian transport as a relatively passive upper part of the Hagar Bjerg Thrust Sheet.

The major part of the succession (apparently >13km) is assigned to the Riphean to Sturtian Eleonore Bay Supergroup which is dominated by shallow marine siliciclastic sediments, and capped by carbonates of the Andrée Land Group (Sønderholm & Tirsgaard 1993). The disconformably, locally unconformably, overlying Tillite Group (Vendian; 800–1000m) includes two diamictite units, the Ulvesø and Storeelv Formations (Hambrey & Spencer 1987). The upper part of the Vendian is absent and the Cambrian–Ordovician Kong Oscar Fjord Group (Smith *et al.* 2004) rests unconformably on the Tillite Group with a maximum thickness of over 4km before it is unconformably truncated by post-Caledonian Devonian molasse (Smith & Bjerreskov 1994). The preserved succession of the Neoproterozoic Eleonore Bay Supergroup is *c*.3.5km thick in the Petermann Bjerg region and, although much thinner, can be correlated with the Nathorst Land Group and basal part of the Lyell Land Group of the Eleonore Bay Supergroup of the fjord region (Smith & Robertson 1999). Likewise, the Kong Oscar Fjord Group strata deposited in the fjord region were much thicker than the equivalent 220–400m thickness of strata deposited on the Greenland craton and preserved in the foreland windows.

Implications for restoration of the Laurentian margin

Recognition of the stacking of major thrust sheets above foreland windows in the southern half of the East Greenland Caledonides forms the basis for the restoration of a Caledonian WNW-directed foreland-propagating thrust sequence (Higgins & Leslie 2000). The Niggli Spids Thrust Sheet must have originated from areas formerly ESE of the foreland windows; the Hagar Bjerg Thrust Sheet must have been derived from areas still farther to the ESE. The thick Neoproterozoic–Lower Palaeozoic succession of the Franz Joseph allochthon is envisaged to have initially been carried passively westwards on top of the Hagar Bjerg Thrust Sheet. WNW-displacement of the underlying Hagar Bjerg Thrust Sheet relative to the Niggli Spids Thrust Sheet was at least 100km, and WNW-displacement of the younger, structurally underlying, Niggli Spids Thrust Sheet was in excess of 90km with respect to the foreland. There are no constraints on the maximum total thrust displacement, although up to 400km was suggested by Higgins & Leslie (2000).

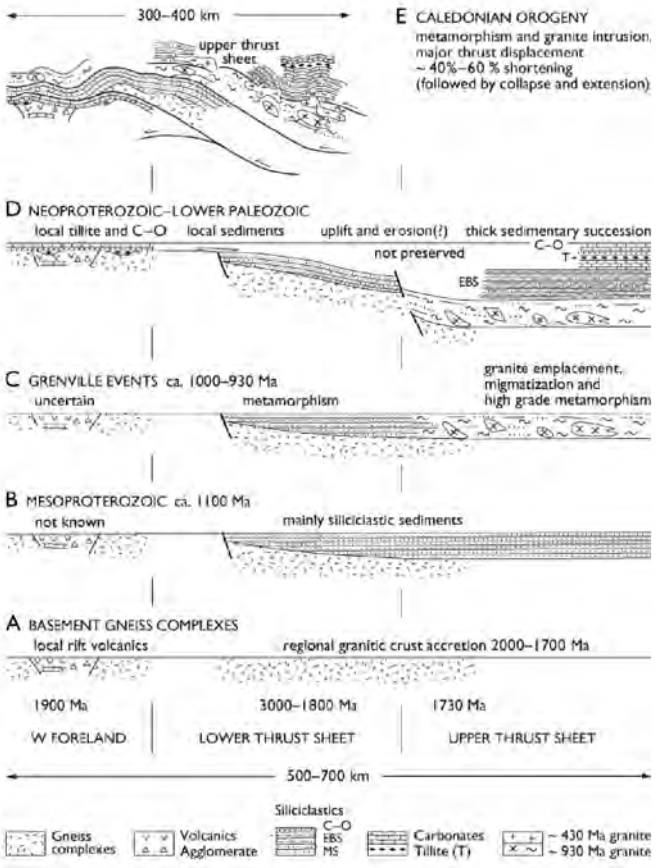

Figure 7. Interpretative restoration of the Niggli Spids and Hagar Bjerg thrust sheets to their original relative positions east-south-east of the foreland windows provides insights into the geological history of a 500–700km wide zone of the north-east margin of the Laurentian shield in East Greenland (A–D). Caledonian thrusting reduced this zone to the present *c*. 300km wide orogenic belt (E). EBS: Eleonore Bay Supergroup. C-O: Cambro-Ordovician Kong Oscar Fjord Group. T: Tillite Group. Modified after Higgins & Leslie (2000).

In the reconstruction of Figure 7 (A–E), the observations from the various lithotectonic divisions are assembled into five time slices. Present outcrop dimensions of the Niggli Spids Thrust Sheet and Hagar Bjerg Thrust Sheet are assumed to relate to their original extent on the pre-Caledonian Laurentian shield. The schematic west to east cross-section of the reconstructed onshore region of the Laurentian margin in Figure 7 is thus estimated to be at least 500km, and possibly as much as 700km wide at the outset. The principal lithostructural segments are reviewed below, along with pointers toward the comparable lithotectonic units of the Scottish Caledonides, more details of which can be found in the excellent review of Strachan *et al.* (2002).

The basement gneiss complexes of the restored East Greenland margin contain the same broad range of Archean to Palaeoproterozoic complexes known from the Laurentian cratonic shield of western and southern Greenland (Henriksen *et al.* 2000). Rift-related pre-1900Ma Palaeoproterozoic volcanic and sedimentary rocks are preserved locally in the foreland only. The parallels with the Scourian and Laxfordian Gneisses and with the Loch Maree Group of the NW Scottish Highlands Lewisian Complex are striking.

Thick earliest-Neoproterozoic meta-sedimentary rocks (Krummedal sequence) are widely distributed in both the Niggli Spids and Hagar Bjerg thrust sheets, but there is no evidence that they were ever deposited in the western foreland areas. The Krummedal successions are exposed over a N–S distance of at least 600km in East Greenland. Figure 7 suggests that the original depositional basin was at least 300km wide; the eastern limit is undefined. Successions of comparable age in Spitsbergen (Gee & Teben'kov 1996) and the NW Highlands of Scotland (Moine Supergroup; Holdsworth *et al.* 1994), suggest that the 'Krummedal basin' may be part of a widespread system of earliest Neoproterozoic Laurentian sedimentary basins. Moine Supergroup and Krummedal succession detrital zircon populations share similar age spectra (Friend *et al.* 2003; Kalsbeek *et al.* 2000; Watt *et al.* 2000); both were deposited after *c.*1050Ma, the age of the youngest zircon found.

Krummedal deposition must have preceded early Neoproterozoic tectonothermal activity. The suite of 940–910Ma augen granites and leucogranites is widely distributed within the Krummedal sequence of the Hagar Bjerg Thrust Sheet over a N–S distance of more than 400km. In Spitsbergen, 970–940Ma augen granites are emplaced synchronous with an episode of deformation (Johansson *et al.* 2000), a scenario resembling that of the Renland region of East Greenland (Leslie and Nutman 2003). The position in Scotland seems less clear, since zircon dating studies record a number of HP/HT tectonothermal events between 840 and 730Ma (see review in Strachan *et al.* 2002; Tanner & Evans 2003). East Greenland seems to record orogenic activity which succeeds the Grenville (Elziviran) events of North America, and may record gradual northwards movement of Baltica along the Laurentian margin during final locking up of the components of Rodinia (Weil *et al.* 1998).

The Upper Neoproterozoic and Lower Palaeozoic successions attain an apparent maximum thickness of 18.5km in the Franz Joseph allochthon and attest to a depocentre which must have been at least 600km long and a minimum 200km in width. The broad similarities of the Eleonore Bay Supergroup of East Greenland and the Murchisonfjorden Supergroup of Spitsbergen are well known and were recognised by the earliest explorers (e.g. Nathorst 1901). Strong correlations can readily be drawn between the Eleonore Bay Supergroup and the Grampian Group and Appin Group Dalradian of the Scottish Central Highlands (e.g Sønderholm & Tirsgaard 1993). There is a very close correlation between the Tillite Group of East Greenland and the equivalent sequence of Spitsbergen (Hambrey and Spencer 1987); tillites are of course well represented in the Dalradian of Scotland and Ireland (Harris *et al.* 1994). The siliciclastic to carbonate sediments of the Cambrian–Ordovician Kong Oscar Fjord Group were deposited on a steadily subsiding platform. Early Palaeozoic platform correlations over distances of thousands of kilometres along the Laurentian margin of Iapetus are well known (e.g. Swett & Smit 1972). Generations of geology students are familiar with the Cambro-Ordovician foreland succession of the NW Highlands of Scotland, with its distinctive "Pipe rock".

The Caledonian Orogeny in East Greenland was the result of the final convergence of Baltica with Laurentia. There is scant evidence in the East Greenland Caledonides, of the short-lived Lower Palaeozoic marginal arcs and basins which must have accommodated subduction of Iapetan oceanic crust and convergence with Baltica. These exotic terranes were mainly incorporated as Scandian thrust sheets into the higher structural levels of the Scandinavian Caledonides (Yoshinobu *et al.* 2002). The youngest sediments preserved in the Franz Joseph Allochthon are of Mid-Ordovician age (*c.*460Ma; Smith & Bjerreskov 1994) while Iapetan margin carbonate sedimentation persisted into the early Ludlow (422Ma) in northernmost East Greenland (north of 79°N). Silurian turbidites, derived from the erosion of the rising Caledonian mountain chain (Hurst *et al.* 1983), brought carbonate deposition to an end; the youngest turbiditic shales overidden by Caledonian thrusts in east North Greenland (Middle Wenlock age, *c.*425Ma) provide a maximum age for these frontal thrusts.

The earliest known Caledonian granitoid rocks crop out in the Hagar Bjerg Thrust Sheet in the southern part of the orogen and are I-type Caledonian calc-alkaline granodiorites and diorites, dated by SHRIMP U-Pb zircon analysis to between 466Ma±9Ma and 432±10Ma (A P Nutman & F Kalsbeek, unpublished data). The older date is close to that of the youngest sediments preserved in the Franz Joseph allochthon suggesting tectonic control on sedimentation on that part of the Laurentian margin closest to eastward subduction of Iapetan oceanic crust during the Taconian-Grampian phase of arc accretion. The Silurian record of deep-seated high temperature metamorphism, ductile extensional shearing and I–type magmatism in Renland (*c.*430Ma, Leslie & Nutman 2003) suggests westward-directed Silurian subduction of remnant Iapetan oceanic crust followed earlier eastward subduction and arc accretion events. Supra-subduction processes preserved in allochthonous units in East Greenland must have been relatively short-lived before the final encroachment of Baltica and the ensuing continent-continent collision.

Early Silurian (Scandian) crustal thickening and collision resulted in formation of S-type Caledonian granites in East Greenland at 435–425Ma. Although there is convincing evidence of some syntectonic granite formation, Caledonian granites and migmatites are abundant in the Hagar Bjerg Thrust Sheet, but conspicuously absent in the underlying Niggli Spids Thrust Sheet. Thrusting clearly postdated most of the granite and migmatite formation preserved in the Hagar Bjerg Thrust Sheet. More deformed granite sheets may have formed contemporaneously with thrusting around 425Ma in the Fjord region of East Greenland, perhaps somewhat later than the main movements on the Moine Thrust belt of the NW Highlands of Scotland and thus emphasizing the tendency for diachroneity of comparable events along the Caledonian orogen.

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The crater lake lahar hazard on Mount Ruapehu

Philip Clark

When in New Zealand in 2003, I visited the Visitors' Centre in the Tongariro National Park, at the foot of the active volcano Ruapehu. As I was thinking of a possible project for SXG390, Geohazards, I was intrigued to see some leaflets on the Ruapehu Crater Lake Lahar hazard. The next day I was in conversation with an old man on a campsite who told me his life story. Eventually we worked back to Christmas Eve, 1953, when the Wellington-Auckland express train plunged into the River Whangaehu at Tangiwai, 42km downstream of the river's source in the Crater Lake on Ruapehu. The railway bridge had just been destroyed by a catastrophic mud flow ("lahar") from the lake. 151 people were killed, New Zealand's second worst natural disaster. The old man told me that he had been the guard on that train, but had fortunately with his mate the driver handed over to the next shift at the previous station. This had to be my project! And this is a version of the project shorn of the attempt to be a "scientific paper", a "literary review" (a very worthwhile exercise, I warmly commend SXG390!)

Lahars are common on Ruapehu, and many of these flow down the Whangaehu catchment. The 1953 event ("Tangiwai 1953") was unusual in that the lahar was caused by a breach in the natural dam of the crater lake. This caused a sudden outpouring of water with an exceptionally high peak flow. Most lahars from Ruapehu are primary, caused by steam eruptions or small-volume magmatic episodes mobilising tephra lying on the snow or ice near the summit. A smaller number are secondary, triggered by rain.

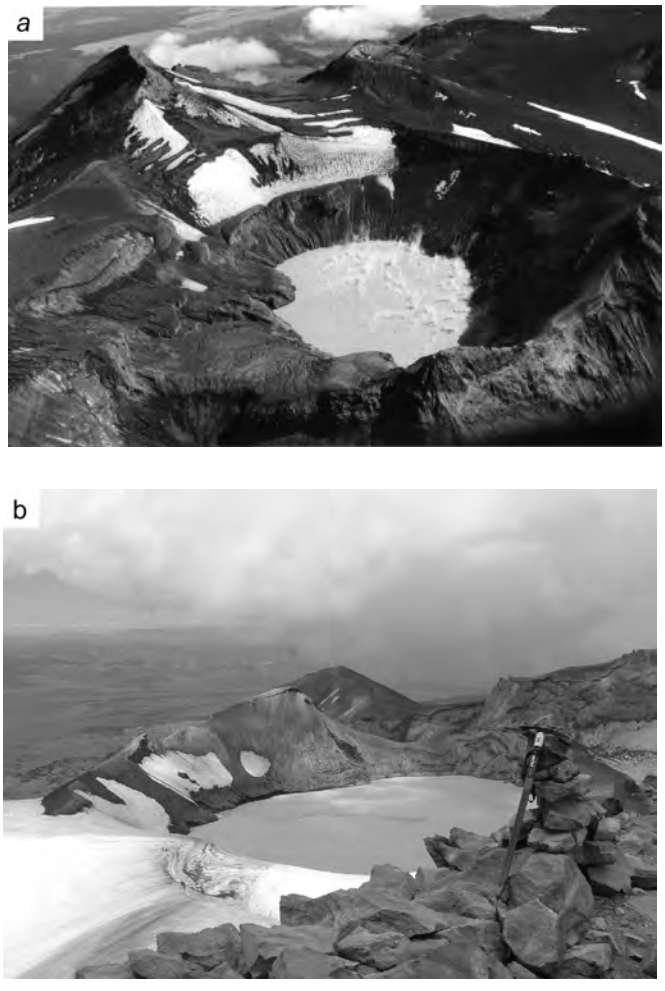

Figure 1. a) Ruapehu crater lake 1999, outlet foreground left, © J B Clarke; b)Ruapehu crater lake 2003, outlet to right of cairn with ice axe, © A D Gordon-Clark.

Ruapehu is a much-studied and very active volcano, but possible re-occurrence of the rare hazard of a *catastrophic* lahar was ignored until 1996, when the Crater Lake, recently emptied by a series of eruptions, began to refill. An insubstantial barrier of unconsolidated tephra had formed on top of the lava wall at the lowest point of the crater rim. It was perceived that this might give way when the lake fills to that height. The photographs in Figures 1a & 1b taken in 1999 and 2003, show the lake gradually filling. The New Zealand Department of Conservation (DOC) initiated an environmental and risk assessment for mitigation (ERAM) of the hazard of a lahar involving substantial emptying of the Crater Lake, from a number of possible causes. The report appeared in 1999. Subsequent minimal action was taken. Other options, involving more intervention than was thought desirable in a National Park and World Heritage Site, were not proceeded with.

Mount Ruapehu

Mount Ruapehu is a large, highly active, dominantly andesitic stratovolcano situated at the southernmost point of the Taupo Volcanic Zone (TVZ). This is the currently active volcanic area in New Zealand, associated with the subduction of the Pacific Plate's oceanic crust under the Indo-Australian Plate's continental crust and consequent arc magmatism. The TVZ stretches 250 km north-north-east from Ruapehu through Lake Taupo and

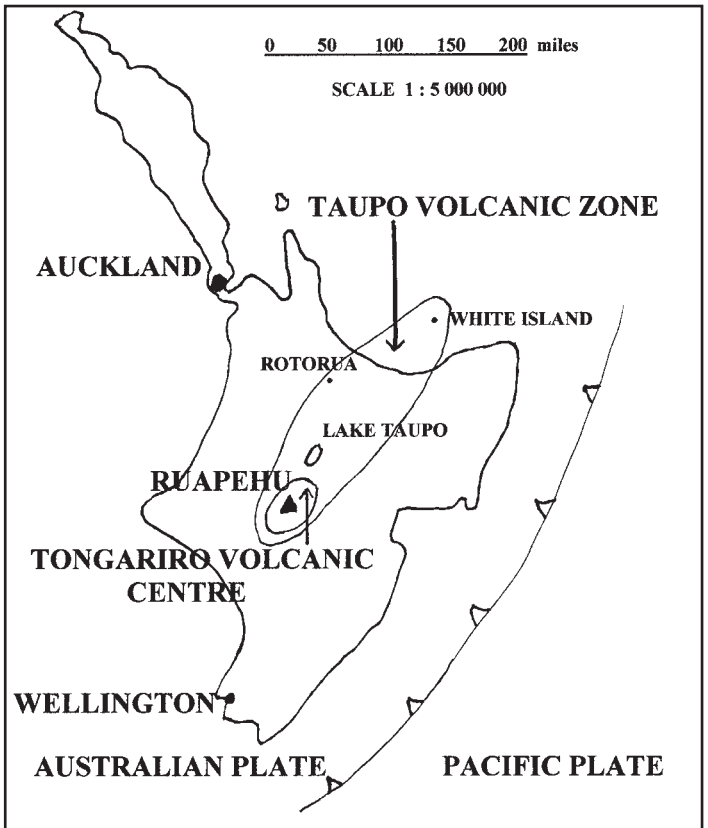

Figure 2. Map of North Island, New Zealand, to show tectonic setting of Mount Ruapehu.

Rotorua to White Island, an extremely active new volcano out in the Bay of Plenty (Map: Figure 2). The Tongariro Volcanic Centre, the southern end of TVZ, has been active since ~1Ma; Ruapehu has been active for ~250ka. The present active vent dates back 2500 years. Ruapehu is 2797m in height, and therefore although in comparatively low latitudes (39^{o}20'S) snow and ice permanently mantle a broad, irregular summit region 3 x 1.5km.

The active crater is normally filled by a lake; this was not discovered (by Europeans at any rate) until 1879. That was 18 years after an explosion said at the time in a New Zealand newspaper to have been the first "for a period beyond the recollection of the oldest inhabitant". In 1886 the lake "was occupied by a great sheet of ice, and there was no appearance of steam or water", but only a few months later the ice had melted and the lake was steaming. The temperature normally varies nowadays between 18^{o}-40^{o}C. The lake normally contains ~9x10^{6}m^{3} of highly acidic water, and is ~500m in diameter with an outflow at 2530m. The lake emptied in 1945 through upwelling of andesitic lava and in 1995/6 from phreatic and phreatomagmatic eruptions. Normal drainage, besides seepage through rim walls, is over a lava sill through a stream/ice cave outlet where the rim is lowest to the south-east, into the Whangaehu catchment. Since 1945 a thick bed of mud has sealed the lake floor and prevented the water percolating into the ground-water system

Crater lakes and lahars

Crater lakes

Crater lakes exist on >12% of active volcanoes. They are mainly caused by accumulation of rain; on snow-covered volcanoes also by melting snow and ice (the biggest reason on Ruapehu). On active volcanoes their existence needs almost impermeable crater walls and floors, hence crater lakes are more commonly found on andesitic volcanoes and where there is a large proportion of fine ash. There may be a contribution from ponding of steam from fumaroles in the crater (vents emitting steam, gas, volatiles), basically caused by recycling of heated atmospheric water. Commonly crater lakes do not overflow, and if small are both fed by and drain into the ground-water system. The formation of lahars is the main hazard from crater lakes.

Lahars

These are frequently loosely described as "dense mudflows". A more precise description by Smith & Fritz (1989) has become classic: "a rapidly flowing mixture of rock debris with water, with a solids content greater than that of normal streamflow, from a volcano". The two main types are hyperconcentrated streamflow (20-60 vol% sediment) and debris flows (more highly concentrated mixtures of sediment and water). The latter normally transform downstream into hyperconcentrated streamflows as some of the sediment settles. Much of the debris is "tephra" (all fragmented material ejected from a volcano, from ash to boulders), which becomes water-saturated and remobilised. Lahars being gravity-driven soon enter stream channels and only spread beyond banks when gradient lessens.

Lahars vary enormously in their phenomena. The average distance up to which effects are experienced is ~10km; the maximum is 300km and occasionally more. The average area affected is 5-10km^{2}; it can be 200-300km^{2}. The average velocity is 3-10 ms^{-1}; the maximum 30+ms^{-1}. Temperature can vary from cold to >100^{o}C.

Crater lake lahar hazards

Most crater lake lahars are caused by "phreatic" or "phreatomagmatic" eruptions (generated by interaction between hot magma and water, the latter including ejection of significant amounts of magmatic material). On snow- and ice-covered volcanoes, like Ruapehu, hot water ejected from the crater perturbs mantles of snow and ice and remobilises tephra in a variety of complex sedimentary syn- and post-eruptive responses (the series of 1969 eruption-caused lahars on Ruapehu is the case study used by Major and Newhall (1989) for lahars of this sort).

These responses span nine orders of magnitude and time frames of minutes to years. Where there is a crater lake on an active volcano, lahars are more likely, because of phreatic/phreatomagmatic eruptions which can disturb and remobilise the tephra. Occasionally crater lakes empty, this being either eruption-related or through collapse of natural dams, usually causing serious lahars from the volume of water, although crater lakes can empty without causing lahars. Where the volcano is also covered with snow and ice there is a larger amount of potential water to swell the lahar.

Lahars from crater lake dam collapse

This is comparatively rare: of 10 crater lake lahars which caused >100 deaths since 1500, all were associated with eruptions except those from Agua (Guatemala), 1541, and Tangiwai 1953. There is currently one other possible threat of a dam collapse, at Lake Nyos (Cameroon), although unlike the Ruapehu dam that at Nyos may be >100,000 years old. Tangiwai 1953 was the only example in modern times of a lahar caused in this way, and this hazard at Ruapehu, as said above, only became apparent again after the 1995-6 eruptions. The rarity of dam collapse lahars makes it necessary to study large prehistoric occurrences to understand fully the lahar hazard today.

Ruapehu lahars

Ruapehu and geological study

The historical record in New Zealand is of course very short, and so the geological record has been analysed more extensively in the TVZ than perhaps anywhere else to supplement the deficiencies. Despite lacunae in the record evidence has been found of many past catastrophic lahars, as the deposits are quite distinct. On Ruapehu, eruption lahars of ~10^{6} m^{3} occur every twenty years on average. According to the sedimentary record, lahar events from all causes of 10^{6}-10^{7}m^{3} have occurred every 50-100 years over the last 1850 years. Lahar events of >10^{7}m^{3} recur every ~270 years.

Ruapehu (Figure 3) is a much-studied volcano, and important aspects of lahars have been made clearer by some of these stud-

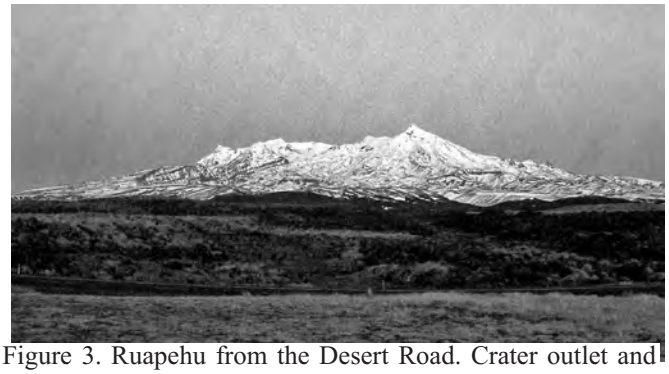

Figure 3. Ruapehu from the Desert Road. Crater outlet and Whangehu catchment extreme left of the rim. © A D Gordon-Clark.

ies. The interactions on snow- and ice-covered volcanoes at mid to high latitudes, causing lahars, between crater lake water, expelled in phreatic and phreatomagmatic eruptions, and saturated freshly erupted tephra are now better known from Ruapehu studies. Rain-triggered lahars were well known on tropical volcanoes but not much recognised on snow-covered volcanoes at higher latitudes. Their sedimentology and flow behaviour in the latter circumstances are now known from Ruapehu studies. Lahar flow behaviour in general has been also studied in detail on Ruapehu.

The possible ways of crater lake dam failure have been studied more intensely at Ruapehu than elsewhere. All these studies have been made both for reasons of general scientific enquiry and latterly to study the hazard of a possible future catastrophic lahar involving Crater Lake water, as happened in 1953.

Effects of largest recent lahars on Ruapehu

In 1953 the collapse of the barrier when the water was significantly above the lava sill released ~1.8x10^{6}m^3 of water into the Whangaehu catchment (Figure 4). The resulting lahar travelled at ~17kmhr^{-1} and reached Tangiwai in ~2.3hrs, where the water level rose ~6m. After sweeping away the railway bridge and train, the lahar then damaged the road bridge downstream, and its approaches. The next major lahar was in 1975 when a lahar from phreatomagmatic causes totalled ~2x10^{6}m^3 (lake water, melted snow and ice, and remobilised tephra). The water rose ~3.9m at Tangiwai with little damage to the bridges; two smaller bridges downstream were destroyed. In the prolonged eruptions of 1995-6 the largest of a number of phreatomagmatic lahars destroyed the Whangaehu footbridge on the Round-the-Mountain track. The water rose 2.6m at the lahar warning gauge 10km upstream of Tangiwai where no damage was done.

Peak flows and destructive effect

The magnitude of peak discharge is the most significant factor, more so than the total volume of the lahar, in the destructiveness at Ruapehu of both prehistoric and historic lahars. Some prehistoric lahars are estimated to have had considerably higher peak flows than the two highest of 1953 and 1975. It has been estimated that in 1953 the peak flow at the top of the alluvial fan 9.5km from the crater lake was 805±180m^{3}s^{-1} and at the Tangiwai bridges, 42km distant, 590±110m^{3}s^{-1}. In 1975 the peak flow at the Tangiwai bridges was observed to be 415-580m^{3}s^{-1} and in 1995 232-360m^{3}s^{-1}. The worst-case scenario expected is 1940±400m^{3}s^{-1} at the top of the alluvial fan, slackening to 1535±300m^{3}s^{-1} at the bottom of the fan, 15.5km from the crater, and 910±105 m^{3}s^{-1} at Tangiwai – comparable to 1953.

Predictability of the effects of lahars

Studies of lahar behaviour and especially of lahar hazard delineation zones show that areas at risk can be predicted, because flow paths from lahars can be mapped with high accuracy. The effects are thus to a considerable extent quantifiable. It is therefore clear that a catastrophic crater lake lahar on Ruapehu will cause sudden rises (<11m) of turbulent boulder-laden water travelling at <25kmh^{-1} to flow down the Whangaehu. Without engineering works, up to 2.7% of a "worst-case" dam-collapse lahar, with a peak flow at the top of the alluvial fan of 1540-2340m^{3}s^{-1}, might spill over into the Waikato stream at the fan, reach the Tongariro River and flow north into Lake Taupo.

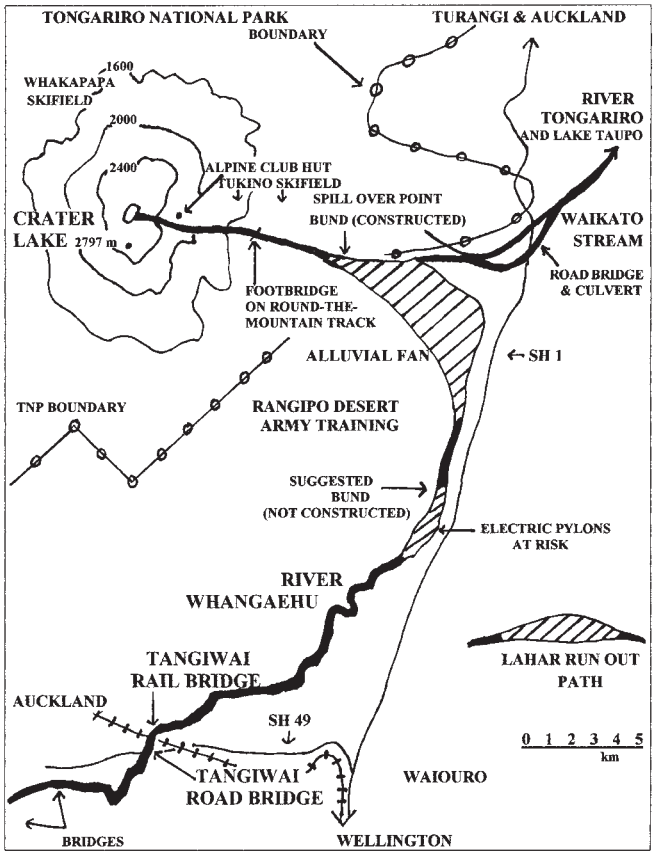

Figure 4. Map of Mount Ruapehu and surrounding area, to show Crater Lake lahar.

Hazards from a Ruapehu crater lake dam collapse lahar

There are two main hazards from a major lahar on Ruapehu (however caused): damage to life and installations; ecological damage from Crater Lake water.

Threats to human safety

The lahar routes in both the Whangaehu and Tongariro catchments are in very thinly populated areas, except for the town of Turangi near where the Tongariro river flows into Lake Taupo, and that is not currently at risk from lahars (although there have been prehistoric ones in the town area). Persons at risk include any tourists, skiers, or DOC staff in the Tongariro National Park close to the Whangaehu – these would have at least 5 minutes' warning from the noise audible 2km distant. Army personnel train in the Rangipo Desert (the area made famous in the film *The Return of the King*!), but would not be allowed access during the risk of a collapse lahar. Power workers at the Poutu and Rangipo intakes could be at risk if working near the Tongariro. The maximum number of people at risk before the recent measures were taken was estimated at ~20-~50.

Lahars in the Whakapapa catchment to the west have only been recorded in 4 years since 1895. (This is partly because the prevailing wind is from the west.) Although the greatest number of people would be at risk because of the important Whakapapa ski field, these lahars would not involve major emptying of Crater Lake water and so are not part of the focus of this study.

Threats to installations
A catastrophic lahar on the Whangaehu would (above the alluvial fan where the gradient lessens) only destroy the footbridge on the Round-the-Mountain track. The Tukino ski field installations are well above the lahar path. There would be a threat to national electrical grid transmission pylons 25km downstream where a worst case lahar would put these at risk but not State Highway 1 (SH1) a few hundred metres to the east. (The Wellington to Auckland rail and road routes diverge at Waiouro south-east of Ruapehu, the railway going round to the south and west, the road up the east side of the massif across the Rangipo Desert and onto the top of a low scarp above the level of a lahar spreading over the fan.)

The main destruction would again come at Tangiwai, 42km downstream, where a peak flow of 800-1000m^3s^{-1} would threaten the bridges on the railway and State Highway 49, the memorial structures to the 1953 disaster, and two bridges further downstream. However, an overspill lahar into the Waikato would threaten a culvert and road bridge further north on SH1 and might affect hydroelectric structures on the Tongariro River.

Ecological damage
This would be chiefly caused by a sudden influx of Crater Lake water with a very different chemistry to the normal stream. Ruapehu is one of the handful of crater lakes where the precise chemical composition is known, the lake chemistry being relevant not only to eruption predictability but also to lahar ecological effects. This effect would be minimal in the Whangaehu, the normal overflow and seepage route from Crater Lake and the preferred path for lahars. There is no fish life and little invertebrate life in its upper reaches.

But if the lahar overflowed into the Waikato (especially in the worst case if Crater Lake water was permanently rerouted into the Waikato) the ecological consequences for the Tongariro River and even for Lake Taupo downstream, both high quality freshwater systems, could be devastating. As said above, very few lahars have flowed into the Tongariro in historic times. Aquatic life, including a regionally important population of blue duck and a thriving trout fishery, could be devastated by the acid crater lake water, which would also threaten water supplies for the large town of Turangi and further afield.

Hazard assessment and mitigation at Ruapehu
Hazard assessment before the 1995-6 eruptions, at Ruapehu as on other snow-covered volcanoes, was predicated around the hazards arising from primary lahars associated with syn-eruptive melting of summit ice caps. The events of 1995-6 showed that as well as the threat of a crater lake dam collapse, secondary lahars from tephra remobilisation, especially rain-triggered ones, were as significant**.**

Since the early 1970s hazard assessment world-wide has placed emphasis on warning systems, and the requirement to make applied volcanology sensitive to the characteristics of local demography, economy, culture and politics. Volcanologists are expected to, and are eager to, cooperate closely with relevant authorities. Following the 1996 Ruapehu eruption events these considerations were given priority in the assessment of possible mitigation. A significant consideration was that Tongariro was the first National Park in New Zealand, and since 1990 it has been a double World Heritage Site. This is for its environmental value and for its cultural significance to the Maori people.

Crater lake lahar issues relevant to mitigation
The event is extremely fast and demands sudden and rapid reaction in less than two hours. The event's timing is predictable, within a period of weeks or months after the lake reaches the tephra barrier. Although the exact size of the expected lahar is unpredictable, the 1953 lahar enables a worst-case scenario to be established. There are high levels of public expectation about the event and its outcomes. (These observations were made in a 2004 analysis of the Ruapehu lahar emergency response plan development process.)

The Department of Conservation assessment 1997-1999
The DOC assessment produced a range of risk mitigation options:

1) no engineering intervention, but: land-use planning; improved warning systems (acoustic); response and contingency plans
2) intervention only in lahar run-out zones: one or more containment barriers (bunds), and/or dam(s), at six possible locations
3) hardening or perforating the tephra barrier by various methods: grouting, horizontal tunnelling, culvert, weir, bio-hardening.
4) excavating a trench through the 1995-6 tephra to reduce the lake level (8 possible methods)
5) excavating a trench into the underlying lava at the outlet to reduce the lake level (3 possible methods)
6) siphoning to reduce the lake level, with a barrier truss to slow release of lake water

These possibilities were considered in considerable detail, with likely costs. Two of the possibilities under 3). above have been tried at crater lakes in Java: a concrete weir has been in place for many years at Kawah Ijen, and drainage tunnels have operated at Kelut from 1919 onwards. The latter have been only partially successful and after the 1990 eruptions it was advance warning and not the engineering works which had been renewed again that year which saved lives when the lake emptied again.

Consultation in connection with this assessment
All relevant public authorities and private interests were consulted; an extremely wide range including local government, sports bodies (ski and mountaineering), local and national environment and conservation bodies, bodies representing specifically Maori concerns, the New Zealand Army, the bodies concerned with utilities (generation and distribution of electricity, and railway, highways and transport management), and the Geological Society of NZ representing international volcanology. None thought that the threat made *prevention* of a possible lahar imperative. Excavating a trench through the tephra to reduce the lake level was favoured by a small number; living with the hazard and minimum interference in natural processes was the overwhelming preference. The utilities were largely in favour of a reactive response only. Improved acoustic warning systems and response and contingency plans were of course wanted by all the stakeholders.

DOC assessment recommendations
All the engineering works under options 3-6 above were eventually ruled out in the recommendations of the DOC assessment (although some had been short-listed for further consideration), partly on technical grounds (cost, difficulty, uncertainty of success), and partly on environmental and social grounds. No engineering work was thought acceptable in the summit area, for either the environmental or the cultural heritage situations. The cultural and environmental values of the Tongariro National Park

played a decisive part in the rejection of engineering options in the Crater, more so than reasons of cost.

Option 1 was recommended, with one or more acoustic sensor to give real-time warning, together with continuation of Crater Lake monitoring. The possibility within Option 2 of constructing one bund of the six possible, where the Whangaehu lahar would overflow into the Waikato stream and thence to Tongariro river, was not recommended but not ruled out, and left for further discussion. In 2001 the Minister of Conservation approved the installation of a better warning system, and just the one bund shortlisted above. The Minister declared that no engineering work would be carried out at the crater rim. Before work was carried out, the Ministry of Civil Defence and Emergency Management commissioned a quantitative risk assessment which reported in 2002.

Action taken

Procedures for advance notice (warning signs, track and road barriers, briefing of visitors) are in place. An alarm/response system with three ground sensors (near the lake outlet, near the Alpine Club hut, and near the Tukino Skifield – see Map, Figure 4) has been installed, and the acoustic sensors are fully operative. These will give up to one hour's warning on SH1 and two hours' warning at Tangiwai. The bund has been constructed at the fan/Waikato spill-over.

Responsibilities and Readiness

29 organisations have been assigned responsibilities in the event of the lahar occurring. Alert levels of 30, 20, 10, and 5 minutes have been linked to critical lake levels. Studies show that there is a high state of preparedness involving all relevant agencies. An assessment for the Ministry of Civil Defence & Emergency Management was confident that the measures being taken reduced the residual risk of somebody being killed as a result of the lahar to a less than 10% chance

Conclusion

The current hazard on Ruapehu

The current lahar hazard is perceived as chiefly from collapse of the tephra dam, though other causes of sudden partial or entire emptying of the lake have not been ruled out. Intensive study of lahar behaviour has demonstrated that unless future lahars involve at least partial crater lake emptying they will not have the peak flow which makes the greatest hazard. A lahar with peak flow of $>1900 m^3 s^{-1}$ at the top of the fan or $>900 m^3 s^{-1}$ at Tangiwai would cause at least as much damage to installations as the 1953 lahar.

Crater Lake monitoring has continued, with a site visit roughly once a month. The Crater Lake has not refilled regularly; in the austral winter the level often goes down. It has not filled as fast as expected in ERAM; the lowest likely net estimate given there was a net rate of $50 ls^{-1}$, or $4320 m^3$ per day. This would have brought the lake to the former outlet level by August 2003, but at the end of July 2005 it was still about 1.2m below the hard rock rim and, although it was winter, was filling at ~$2700 m^3$ a day. The danger from collapse of the tephra dam has thus not yet become operative. The most likely time for it was assessed in ERAM as late 2004 to early 2006. In the online NZDOC Crater Lake Status Reports for August 1 2005 it was stated that the predicted time for the lake to reach the tephra dam, when warning level 1b is triggered, is early January 2006 (quite likely), or early December 2005 or late 2006 (less likely). The predicted time for the lake to reach 3.5m against the tephra dam, when warning level 2 (20 minute response) is triggered, is March 2006 or, less likely, late January 2006 or the 2006/2007 summer.

Figure 5. Memorial to the Tangiwai disaster. © J B Clarke

The breaching of the tephra dam when lake water has overtopped the old outlet remains the only highly probable catastrophic event. Dam collapse through tectonic action is rated low to very low. As Ruapehu is a highly active volcano in the active Taupo Volcanic Zone, a large but not catastrophic lahar from phreato/phreatomagmatic causes is a high probability in the near future. This is the only cause likely seriously to affect other catchments than the Whangaehu.

Seriousness of the threat

Lahars on Ruapehu are frequent and there have been no casualties since 1953. The threat to human life before the recent measures was low. The likely damage to installations was as we have seen largely discounted by the relevant authorities in the 1997-9 assessment. Environmental, conservation, and Maori interests were always against any modification of the Crater Lake surroundings. Yet a very comprehensive exercise investigating all possibilities of preventing or mitigating a catastrophic lahar was carried out by the Department of Conservation to produce the environmental and risk assessment report, and after considerable further consultation the Minister authorised more work than this assessment had recommended as the minimum necessary.

Undoubtedly the approach of the 50th anniversary of Tangiwai 1953 was a factor. It is worth asking whether the threat justified the vast amount of investigation and consultation, and the answer must be that a perceived threat needs the fullest response those involved feel necessary. There have been no significant lahars in the Whangaehu catchment since 1999, from any causes, so it is not yet possible to assess the wisdom of the decisions taken in 1999.

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Author

Philip Clark added BSc (Hons) Geosciences from the Open University to long ago Oxford degrees in Modern History and in Theology. Visiting New Zealand in 2003 was up there with visiting the Galapagos in 2001- see OUGS Journal, Vol. 24 (1) "Darwin's Islands".

Post Script

Although on 13 October the level of the lake was slightly below that of the end of July, the most likely date for warning 1b to be activated is now given as mid December 2005, and that for warning level 2 as March-April 2006.

The article above does not say enough about changes in lake level. Very recent work has shown that rises are caused mainly by snow and ice melt and heavy precipitation, but also by input of hydrothermal fluids, rock and ice fall, and thermal expansion. Level falls are due to evaporation, exchange of lake waters back into the vent system, and seepage. These processes are difficult to predict, apart from normal seasonal changes. These over recent years on Ruapehu have often coincided with a near-annual hydrothermal cycle in the lake, obscuring the relative contributions. Snow and ice melt however are dominant, although variable.

An assessment of the geohazard potential of earthquakes in the Tacoma area of Southern Puget Lowland, Washington State

Josephine Brown

Abstract

The city of Tacoma and the surrounding Puget Lowland are situated in southern Puget Sound, Pierce County, Washington State. Historically this area has experienced deep earthquakes but the geohazard potential from devastating Cascadia Subduction Zone and crustal earthquakes has only been fully recognised in the past decade. Analysis of GPS data shows that non-seismic slips within the ductile portion of the subduction interface are periodically stress loading the locked, seismogenic section of the subducting Juan de Fuca Plate. A rupture will eventually occur, possibly with an M9 earthquake. Although published crustal models of Puget Lowland differ in specifics, the consensus is that a major crustal earthquake will happen in Puget Lowland. The periodicity of such earthquakes are longer than historical records, making assessment of earthquake potential and probability difficult. Paleoseismic studies have revealed that the Seattle Fault Zone, 40km to the north of the newly recognised Tacoma Fault Zone, is active. The aim of ongoing research is to discover whether the Tacoma fault zone is also active and if it extends from Puget Sound, on land to Tacoma. The area is urbanised, forested and covered with kilometres of thick glacial and lahar deposits complicating the surveying process. Earthquake-induced geohazards of subsidence, tsunami, landslides, liquefaction, compaction, delta failure and structural damage have occurred in response to past, deep earthquakes. The US Disaster Mitigation Act 2000 requires States, Counties and Cities to produce a Disaster Mitigation Plan before November 2004 and Pierce County is currently preparing such a plan. However, the contents of the earthquake mitigation plan will depend upon the results of a Lidar mapping survey of Tacoma due to take place during autumn 2003.

Introduction

Tacoma, Puget Lowland and Puget Sound lie within the fore-arc of the 1,000km long Cascadia Subduction Zone (CSZ) (Figure 1a), where the Juan de Fuca Plate (JDFP) is subducting obliquely in a NE direction beneath the North American Plate (NAP) (Wells *et al.* 1998).

As with other subduction zones around the World, this area has the potential for earthquakes from three different sources:

1) Subduction megathrust earthquakes

2) Deep (>30km) within-plate earthquakes

3) Crustal earthquakes

Europeans began to settle in north-west Washington 200 years ago (Heaton and Kanamore 1984), and, since then, the only recorded earthquakes to have caused significant damage in Puget Lowland have been from deep sources. The Pacific Northwest was therefore assumed to be relatively seismically quiet until Atwater *et al.* (1995), interpreted tsunami deposits and abruptly buried 300-year-old soils, as evidence of a great subduction earthquake. Japanese tsunami records confirmed the timing of the coincident tsunami to be January 1700, with a magnitude (M) of ~9 on the Richter Scale (Satake *et al.* 1996).

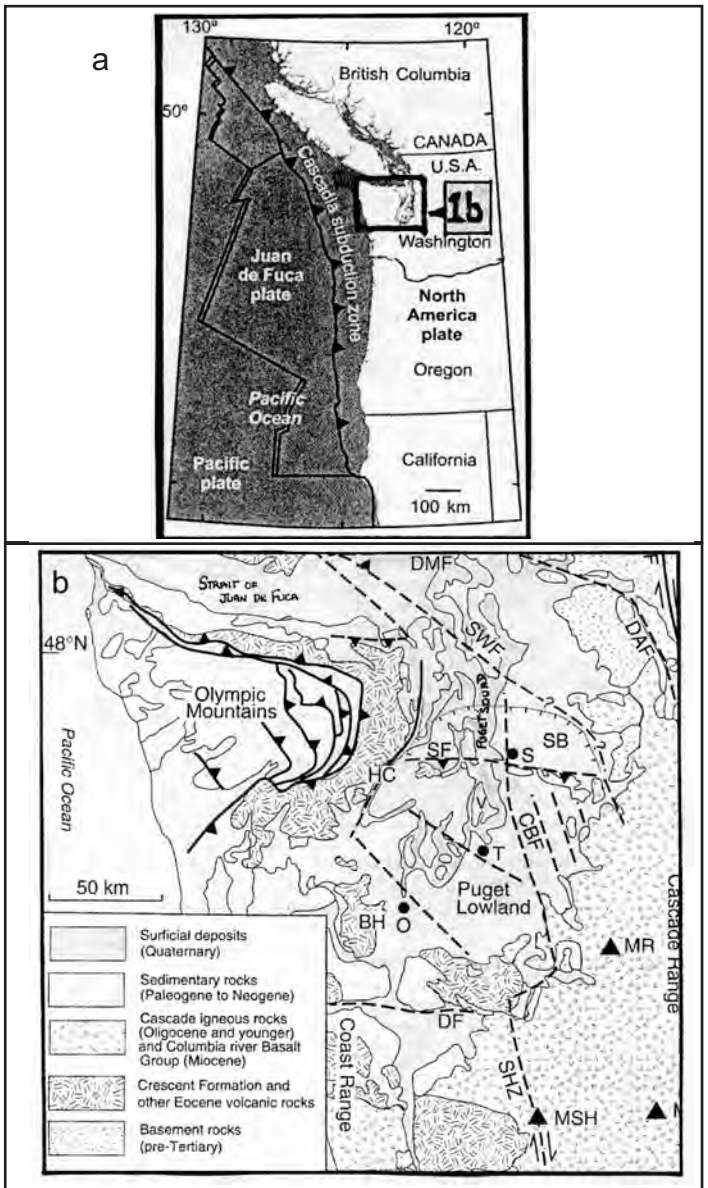


Figure 1. a) Regional Setting of the Cascadia subduction Zone. From Sherrod 2001 Fig. 1a.

b) Schematic geological map of north-western Washington showing fault zones within Puget Sound and Lowland. Adapted from Johnson *et al*. 1999 Fig. 1. The position of the Tacoma fault drawn on this map was prior to Brocher *et al*. 2001. Abbreviations: O – Olympia; T – Tacoma; S – Seattle; SF – Seattle fault; CBF – Coast Range Boundary fault; HC – Hood Canal; MR – Mount Rainier.

Subsequent paleoseismic, geological and geophysical studies have revealed that in addition to E-W subduction stress, Puget Lowland is subjected to N-S crustal compressional stresses, centred across Puget Sound. Fault zones within Puget Sound and Lowland that are known are shown in Figure 1b, but there is little information as to their activity and inter-relationships (Pratt *et*

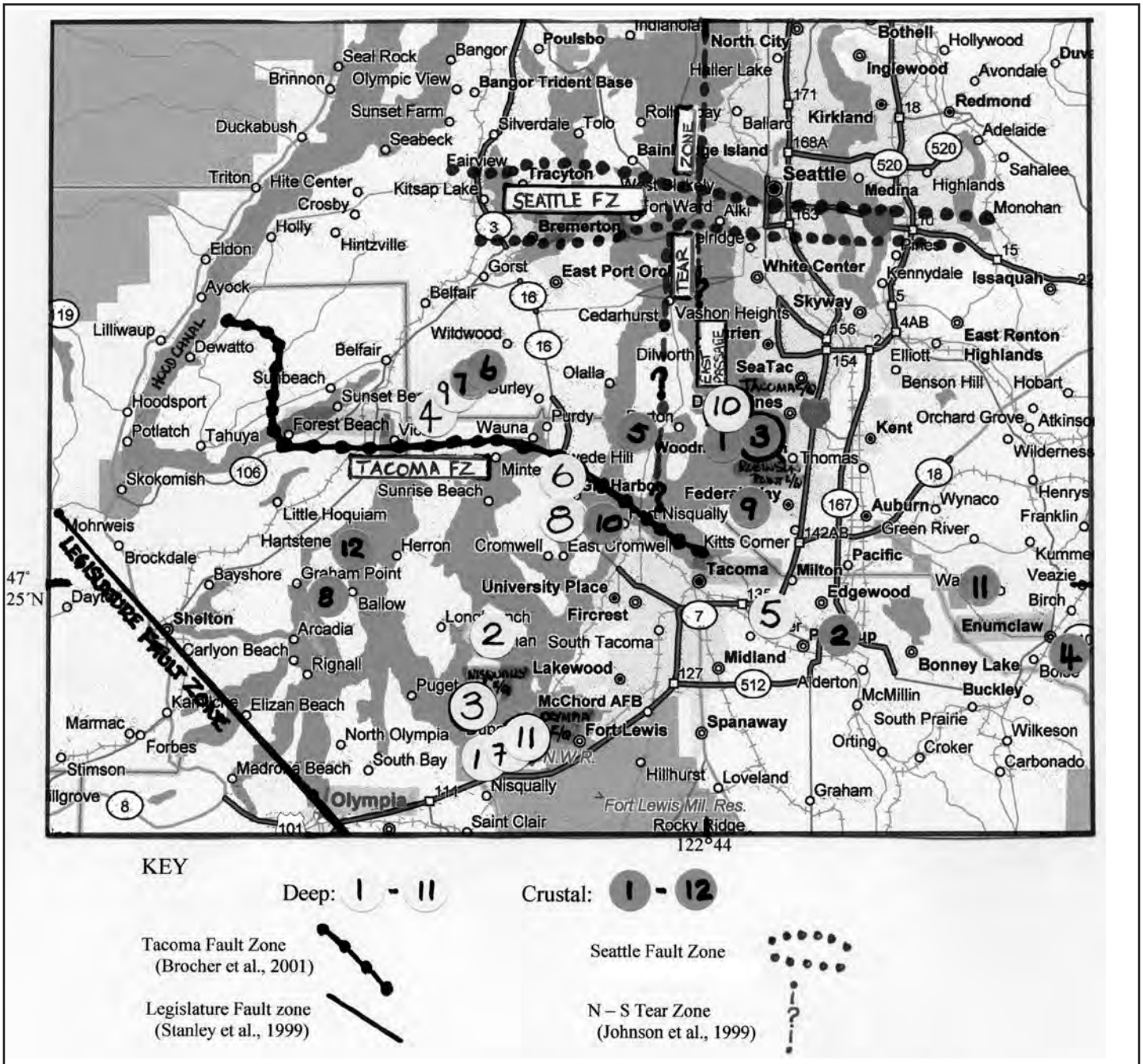


Figure 2. Map of Tacoma to Seattle area (National Geographic Trip Planner1998) with features discussed in this report superimposed upon it.

al., 1997). Consequently, it is crucial for the geometry of the subducting JDFP and overlying crust to be unravelled if the true earthquake potential is to be understood. Several differing Puget Lowland crustal models have been published and these will be reviewed in this report.

Tacoma, Pierce County (Figure 2), a city of 201,000 people is built upon glacial and lahar deposits. Its port, the sixth largest in the USA, is sited upon the artificially filled intertidal delta of the Puyallup River (Gardner *et al.* 2001) (Figure 3). All transport connections to the north and east cross, liquid fuel and natural gas pipe lines pass through and a 500kV electrical line and substation are sited upon the unconsolidated deposits of the river valley (Haugerud *et al.* 2003)(a). Tacoma, at present is ranked in the top 40 US cities for "high-loss potential" and "vulnerability" to seismic risk. Although the seismic hazard has remained fairly constant, seismic risk has increased due to increased urban development (FEMA 2003).

The objectives of this report are to:

- Establish types and depths at which earthquakes have been recorded, or may be generated and investigate known fault zones within Puget Lowland.
- Collate data of past earthquakes.
- Find out what monitoring schemes are in place or planned.
- Investigate the geohazard potential of earthquakes in the Tacoma area and assess the resulting primary and secondary hazards triggered.
- Discuss action being taken by Washington State, Pierce County and particularly Tacoma City to mitigate the geohazard effects of a potential earthquake.

TABLE 1

a) Historic Deep Earthquakes (>30km) within 20km of Tacoma

Figure 2	Date	Magnitude	Depth km	Location	Earthquake Name
1	22.07.01	4.3	52.4	16.3km ENE Olympia	
2	1.03.01	3.4	52.4	21.3km W Tacoma	
3	**28.02.01**	**6.8**	**52.4**	**17.6km NE Olympia**	**Nisqually***
4	18.06.89	4.4	44.8	20.6km SSW Bremerton	
5	11.03.88	3.9	64.7	9.9km ESE Tacoma	
6	18.03.85	3.5	53.3	18.1km NW Tacoma	
7	23.04.75	4.2	45.5	17.8km ENE Olympia	
8	13.01.72	3.6	45.8	15.1 WNW Tacoma	
9	28.11.69	3.5	33.0	19.3km S Bremerton	
10	**29.04.65**	**6.5**	**57.0**	**18.3km N Tacoma**	**Tacoma**
11	**13.04.49**	**7.1**	**54**	**18.3Km ENE Olympia**	**Olympia**

*Nisqually was the first major earthquake to be continuously monitored by GPS (Dragert et al.,2001)

b) Historic Crustal Earthquakes (<30km) within 20km of Tacoma

Figure 2	Date	Magnitude	Depth km	Location	Earthquake Name
1	02.07.99	3.0	24.7	15.1km N Tacoma	
2	04.01.99	3.2	20.3	12.0km ESE Tacoma	
3	**29.01.95**	**5.0**	**15.8**	**17.5km NNE Tacoma**	**Robinson Point**
4	10.09.94	3.9	17.7	2.9km SE Enumclaw	
5	27.04.80	3.7	20.2	18.0km NNW Tacoma	
6	11.03.78	4.8	22.3	17.4km SSW Bremerton	
7	31.03.78	4.1	21.1	17.7km SSW Bremerton	
8	22.02.73	3.8	21.6	25.2km N Olympia	
9	24.10.70	4.1	13.0	11.9 NNE Tacoma	
10	18.01.67	3.3	22.9	12.3 WNW Tacoma	
11	31.12.62	4.7	20.0	8.6km NW Enumclaw	
12	15.02.46	5.8	25.0	28.4km N Olympia	

c) Historic Earthquakes of unknown depth within 20km of Tacoma

	Date	Magnitude	Location
1	19.06.98	4.6	6.5km SW Tacoma
2	23.10.65	4.3	12.0km SSW Seattle
3	19.06.68	4.6	6.5km SW Tacoma
4	15.05.54	5.0	18.9km NNW Tacoma
5	13.11.39	6.2	18.7km S Bremerton
6	30.04.1882	5.7	18.7km S Bremerton
7	12.12.1880	6.0	12.3km SE Bremerton

Data extracted from Pacfic Northwest Seismic Network, Earthquake catalogues (PSNS, 2003).
[http://www.ess.washington.ed/SEIS/PNSN/HIST_CAT/ISOSEISMALS.html]
[http://www.ess.washington.ed/SEIS/EQ_Special/WEBDIR.html]

The research for this project has been Internet based using keywords relevant to the title and tectonics of the area. The US geological and seismological associations and the University of Washington's Pacific Northwest Seismic Network (PNSN) websites have been particularly useful for information on current research and abstracts of recent meetings. The OU Library Database was used to find relevant abstracts of papers published by key people researching Puget Sound's earthquake hazard potential.

Literature review

Since the realisation that the Pacific Northwest is earthquake country, many organisations have been formed to carry out active research into the earthquake potential of Puget Sound and surrounding area. Table 1 gives a list of the most important observed deep and crustal earthquakes for the Tacoma area and those in bold type will be discussed further.

Table 2. Damage from Past Earthquakes

Earthquake	Year	Magnitude, Depth and Damage	Figure 2 Reference
Nisqually	2001	M6.8, 52.4km depth with $500million damage to buildings in southern Puget Sound. Seattle Tacoma International Airport Control tower completely disabled from structural and non-structural damage. King County Airport (Seattle) soil liquefaction and lateral spreading caused runway cracking and holes. Chimney damage the most common damage. (WMD,2003)	Deep No.3
Robinson	1995	M5.0, 15.8km deep. Minor damage in Tacoma, Auburn, and Puyallup with shaking felt throughout western Washington, Oregon and Vancouver. (University of Washington, 1996)	Crustal No.3
Tacoma	1965	M6.5, 57km deep and $12.5million in property damage. Buildings having unreinforced brick-bearing walls with sand-lime mortar most severely damaged. Multi-storey and wood-frame dwellings little damage (Noson *et al*. 1988). Seven people killed and extensive chimney damage. (USGS, 2003).	Deep No.10
Olympia	1949	M7.1, 54km deep and $25million damage to property. Eight deaths. A 0.8km length of 90m high cliff slid into Tacoma Narrows. Railway bridges south of Tacoma thrown out of line. (USGS, National Earthquake Information Centre, 2003). Liquefaction within sand deposits from Mt. Rainier lahars in Puyallup. Landslides and settling of tidal mud flats caused broken water mains in Tacoma (Noson *et al.* 1988)	Deep No.11

Cascadia subduction zone generated Earthquakes

Paleoseismic evidence, together with faulting of Quaternary continental slope deposits (Davis and Hyndman 1989), confirms crustal deformation of the NAP as it overrides the subducting JDFP. Recognition of earthquake-induced turbidites within offshore borehole cores, has shown that 13 CSZ megathrust earthquakes occurred simultaneously along a 600km length since Mazama erupted 7700 years ago, a repeat average of 600 years, the shortest interseismic period being 300 years (Goldfinger *et al.*, 2001). The dynamics of a subduction thrust boundary and the accumulation of strain and its release are simply explained in Figure 4.

No earthquakes have been detected along the CSZ plate boundary, which is atypical for a major subduction zone (Hyndman *et al.* 2001). A network of continuously operating GPS receivers known as PANGA is operational in north-west Washington and provides excellent insight into elastic strain accumulation along the locked plate boundary to millimetre accuracy (Miller *et al.* 2002). E – W on-land compressive strain from subduction has been calculated at ~6.5±1mm/y (Mazzotti *et al.* 2002) across the accretionary prism of the Olympic Mountains.

The western Canadian GPS Array has been operational for 10 years and analysis of data has shown that silent or non-seismic slips do occur on the transitional part of the thrust boundary, (Dragert *et al.* 2001) which adds to the strain of the locked section. There is a periodicity of 14.5 months between events, which last for two to four weeks and appear to release all strain accumulated between slips (Miller *et al.* 2002). Recent analysis has recognised a seismic tremor-like signature called Episodic Tremor and Slip (ETS) which can be used as a real-time stress indicator for the CSZ (Rogers & Dragert 2003).

Although this periodicity has not been recognised across Puget Lowland, during a non-seismic slip event in February 2001, the M6.8 Nisqually earthquake occurred at a depth of 50km (Sumner & Miller 2002).

The wider the locked and transitional sections of the CSZ are, the more energy is released during a rupture (Miller 2001). The closer they are to Tacoma the more damage will be caused to that city. Figure 5 shows that the locked and transitional zones of the arching JDFP are wider and extend further inland towards Puget Sound than elsewhere along its length (Hyndman *et al.* 2001). This arching of the JDFP has significance for both deep and shallow earthquakes in the region.

Deep Earthquakes within the Juan de Fuca Plate

Earthquakes at 30 – 70km depths occur within the subducting JDFP, partly due to phase change with increasing pressure and heat, causing the plate to become denser. Historically this type of deep earthquake has done the most damage in Puget Lowland (Table 2). The cluster of >M5 deep earthquakes in southern Puget Sound (Figure 2), are not seen elsewhere in Washington or Oregon (PNSN 2003).

After extensive seismotectonic studies of north-west Washington, Stanley et al., (1999) suggest that within-slab concentrations of energy release around Tacoma are due to the following:

i) Between 47°and 48.5°N and around 122.4°W (Tacoma: 47.25°N 122.44°W) the JDFP arches, with the dip changing from ~10° to 35° south of the nose of the arch, exaggerated by apparent wrinkles upon the surface of the underlying JDFP.

ii) Concentration of earthquakes coincide with the thickest part of the mafic wedge overlying the JDFP (Figure 6). Assuming that accretionary sediments have been scraped off (Flueh *et al.*

Figure 3. The Puyallup River flowing into Commencement Bay, Tacoma. The area towards which the Tacoma Fault zone is thought to trend.

1998) they infer that this section of the transition interface, between JDFP and the overlying mafic crust, is tightly coupled.

Wong and Harris (2003) have suggested that the subducting slab is cooler at this point, which may lend credence to the above

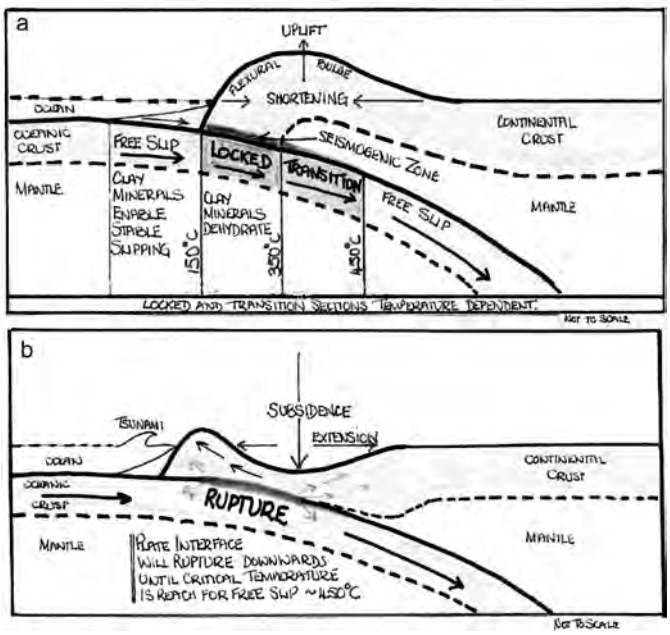


Figure 4. Dynamics of a subduction thrust zone simplified into two states. From Hyndman *et al* (2001) Fig. 3, annotated with information from the paper's text.

a) Interseismic Period (100s years). Elastic deformation builds up between great earthquakes if the thrust fault is locked. The seaward edge of the continent is dragged down and a flexural bulge forms farther landward. The width of down-dip lock is important for seismic hazard for the major population centres located above or near the locked and transition zone.

b) Coseismic Period (a few minutes). When accumulated stress exceeds strength of the locked zone, a subduction thrust earthquake is generated. The seaward edge uplifts and the flexural bulge collapses.

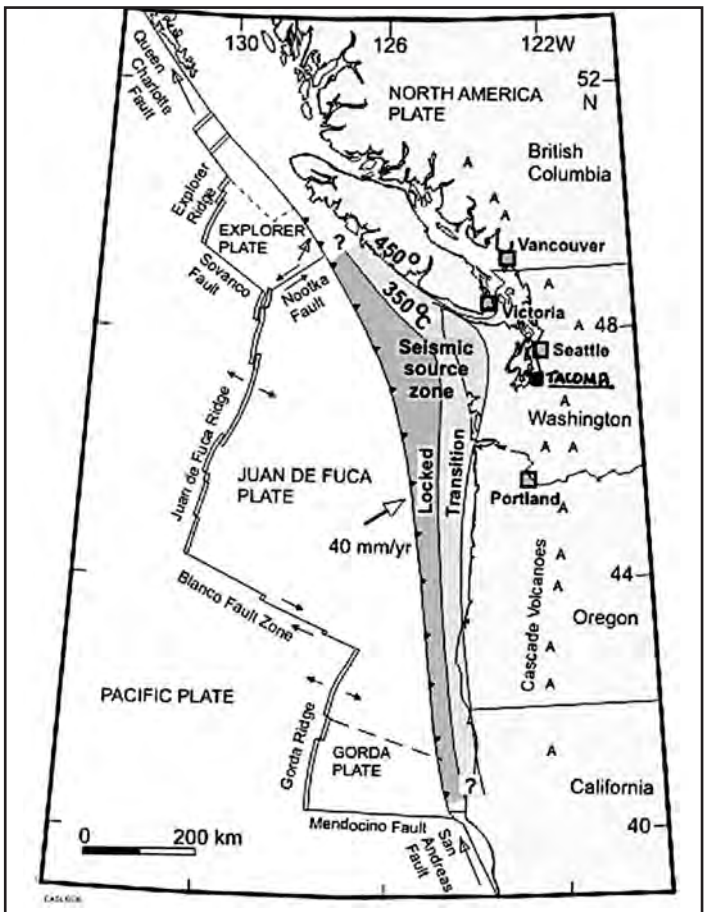


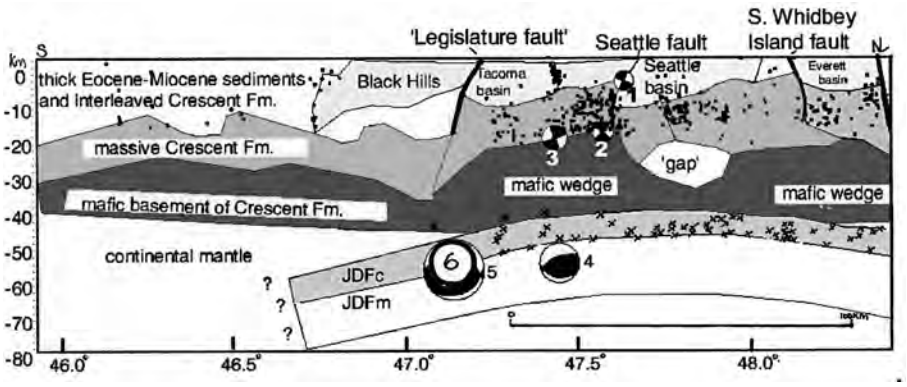
Figure 5. Plan view of the extent of the locked and transition zones on the subduction thrust fault. From Hyndman *et al*. 2001 Fig. 11.

hypothesis. If Stanley *et al.* (1999) are correct in surmising that the JDFP is partially locked to the mafic overlying crust in the Tacoma and Olympia area of southern Puget Sound, the model of Hyndman *et al*.(2001), as depicted in Figure 5, underestimates the distance of the locked portion.

Crustal fault zones underlying southern Puget Lowland

The inter-relationship of known, and possibly unknown crustal faults within Puget Sound are poorly understood. The earthquake potential is therefore still in the process of being quantified by geophysical studies and the production of crustal models. Mapping of the area is very difficult because of thick glacial deposits, forestation and an urban corridor which extends for over 100km from Tacoma to north of Seattle.

Bucknam *et al*.(1992) provided the first evidence that the Seattle Fault Zone was active. They interpreted a 7m uplift of a wave-cut shore platform at Restoration Point, south of the Seattle Fault Zone (SFZ) and minimal subsidence 5km to the north, as an indication that a M7 or larger earthquake occurred on the SFZ, 1000 – 1100 years ago. Corroborative evidence of the dating of the event was provided by: tsunami deposits (Atwater and Moore, 1992); large sediment input into Lake Washington (Karlin & Abella, 1992); radiocarbon dating of trees found within the Lake Washington deposits matched those within tsunami deposits (Jacoby *et al.*, 1992); and rock avalanches on otherwise stable mountainsides (Schuster *et al.*, 1992). However, Bucknam *et al.* (1992) thought that uplift areas of the same period, 23 and 40kms



Focal mechanism for important earthquakes:
NAP crustal: 1) 23.6.97 Bremerton M4.9 (OSU Catalogue)
2) 11.3.78 Port Orchard M4.6 (Yelin and Crosson, 1982)
3) 29.1.95 Robinson Point M5.0 (Dewberry and Crosson, 1996) JDFP slab:
4) 29.4.65 Tacoma M6.5 (Langston and Blume, 1977)
5) 13.4.49 Olympia M7.1 (Baker and Langston, 1987)
6) 28.1.01 Nisqually M6.8 (PNSN Catalogue)
Black dots represent small NAP crustal earthquakes and crosses small earthquakes within JDFP slab.

Figure 6. A geological interpretation of a N -S velocity model through the Puget Sound region, east of Seattle. From Stanley *et al.* (1999) Fig. 44b, annotated with additional information extracted from their text. They interpret the concentration of large JDFP slab earthquakes in southern Puget Sound as being caused by a) combination of double-bending stresses from the flexure of the JDFP slab where dip changes from 10˚ to 35˚ and the position off the southern part of the nose of the arch, b) a locally strong locked thrust updip, c) integrated slab pull forces, d) possible phase change effects.

north-west of Tacoma were too distant to be in response to a slip within the SFZ. Sherrod (2001) also dates abrupt subsidence, 29 and 50km to the south-west of Tacoma as having taken place ~1000 years ago.

GPS studies have shown that N – S compression is accommodated by E – W trending reverse fault zones and uplift like SFZ area (Mazzotti *et al.*, 2002). The N – S contraction of 6-7mm/yr, is similar to shortening across the Los Angeles Basin (Miller et al., 2001). The expectation is that Puget Lowland should experience large upper-plate earthquakes (Wells *et al.*, 1998).

Seismic reflection data and gravity anomaly (Figure 7) maps allowed Pratt *et al.* (1997) to produce one of the first models of Puget Lowland crust (Figure 8a). Their hypothesis was that Puget Lowland lies above a north-directed thrust sheet, the base of which lies at a depth 20km below Tacoma, within the Crescent Formation (CF). Earthquakes along this sub-horizontal thrust could potentially trigger others on the inter-connected system of faults of this thin-skinned thrust model.

In constrast, working with seismic tomographic data from the 1998 Seismic Hazard Investigation of Puget Sound (SHIPS) survey (Figure 9), Brocher *et al.* (2001) suggest that in response to N-S compression, the SFZ works in tandem with the newly recognised Tacoma Fault Zone (TFZ) to raise the Seattle Uplift. Higher relief on the eastern SFZ and the highest relief of the TFZ in the west suggest the strain is being transferred from the SFZ in the east to the TFZ in the west. Their thick-skinned model, (Figure 8b), was based upon one suggested by Wells and Weaver (1993) which shows that both the SFZ and TFZ reach the CF base at ~25 - 30km.

The model of Stanley *et al.* (1999) shows the base of the CF deeper at ~40km (Figure 6), with the SFZ reaching to 20km, similar to Pratt *et al.* (1997). The short fault shown between the Legislature and Seattle Faults (Figure 6), named by Brocher *et al.* (2001) as the TFZ, in contrast reaches only to ~10km.

These three models do not take into account the findings of Johnson *et al.* (1999) of N–S trending, tear fault zone which cuts through the SFZ and Vashion Island trending towards TFZ (Figure 2). This tear zone is thought to be part of a complex dextral sheer zone along which the West Coast Range is moving northward relative to eastern Puget Lowland and the Cascade Range.

A study of historical crustal earthquakes of all magnitudes, separated into depth categories (Figure 10), graphically shows that between 10 – 20km deep, earthquakes seem to trend from the Western Rainier Fault Zone towards Tacoma and at 20 – 30km are more contained within Puget Sound and Lowland (Stanley *et al.*, 1999).

As Earthquake damage is primarily related to magnitude and distance from the rupture, a large crustal earthquake upon the Tacoma fault could have the potential to cause more damage in the Tacoma area than already experienced from deep earthquake sources.

Tacoma Fault Zone

The SHIPS seismic, high-resolution mapping, allowed the TFZ to be identified. The zone is thought to be a south-verging thrust, with the fault dipping northward. The 3m vertical uplift at Lynch Cove (Figure 9) (Bucknam *et al.*, 1992) happens to coincide with the area of highest structural relief on the TFZ. This may suggest Holocene activity (Brocher *et al.*, 2001).

Since the publication of the above papers the technique known as Laser Light Detection and Ranging (Lidar), using an aircraft mounted scanner rangefinder, has been used to investigate Puget Lowland. This enables the production of accurate terrain maps which allow land fault scarps to be recognised (Haugerud *et al.*, 2003b). This type of surveying can "see through the trees", with higher resolution if carried out in the autumn, when the leaves have fallen. Lidar data, together with shallow seismic profiles have shown that a series of shallow faults, in a zone ~7km wide on the western part of the TFZ are trending west to north-west. This may be due to Tacoma fault displacement or shallow faulting related to folding. Whatever the cause, the assumption is that the shallow faults moved during major earthquakes on deeper faults during the Holocene (Crouch J. *et al*., 2003).

It appears, therefore, that the possibility that the TFZ is active is being taken seriously. A USGS led Lidar study of the Tacoma fault is due to take place in autumn 2003, to see if the TFZ can be recognised on land in the Tacoma area. The results are eagerly awaited by Pierce County mitigation planners (Meyers 2003).

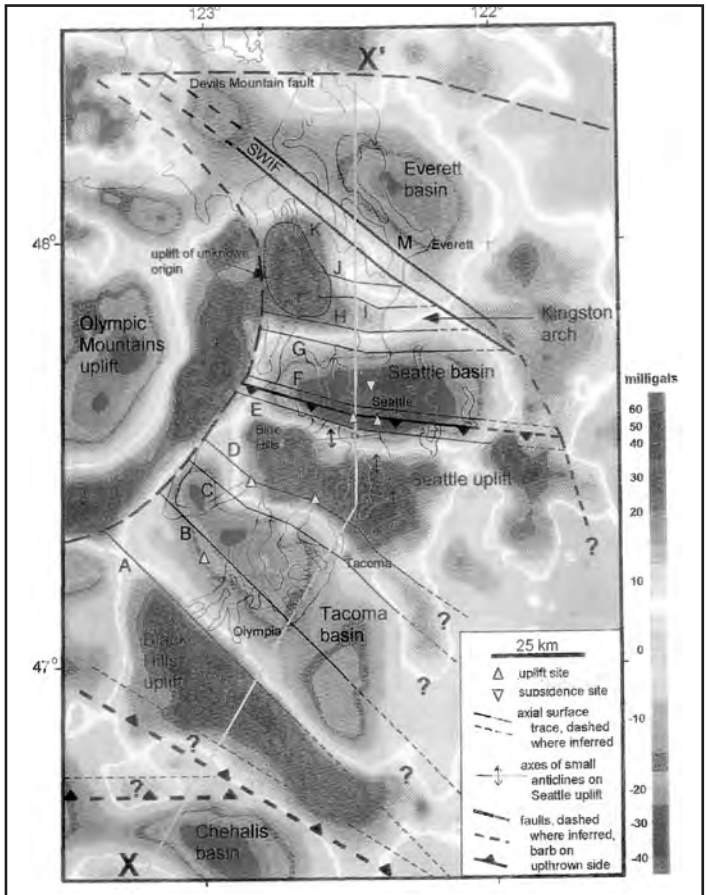


Figure 7. A Bouguer gravity anomaly map of Puget Sound used by Pratt *et al.* (1997, Plate 1) in the formulation of a thin-skinned, thrust sheet model. The gravity anomalies along axial surface A, have remarkably straight boundaries that are interpreted as evidence of structural control of the southern edge of the Tacoma basin. Between C and D, a 10km-wide zone is dipping 15˚ to 25˚south-west along the northern edge of the Tacoma Basin. X – X^{l} represents the cross-section in Figure 8a.

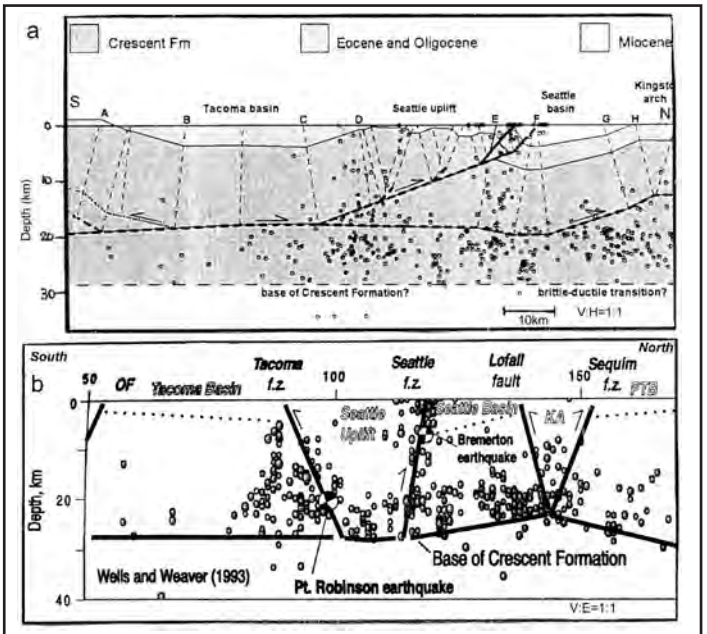


Figure 8. Pratt *et al*. 1997 and Brocher *et al.* 2001 contrasting crustal models for a N – S section through Puget Lowland crust.

a) Pratt *et al*. (1997, Fig. 2) N – S section through Puget Lowland showing their interpretation of seismic reflection data to produce a thin-skinned, thrust sheet hypothesis for the formation of the faults and folds. No major faults are shown delineating the northern edge of the Tacoma Basin. Cross-section represents X - X^{l} on Figure 7.

b) Brocher *et al*. (2001, Plate 8a) favours a thick-skinned interpretation based upon Wells and Weaver (1993), assuming the faults dip moderately to steeply to the base of the Crescent Formation. Analysis of data from the SHIPS seismic survey led to the recognition of the Tacoma fault zone along the northern edge of the Tacoma Basin.

General Effects of an Earthquake

Primary causes

Ground shaking causes damage during an earthquake. Strength depends upon:

i) Magnitude, distance from focal point and duration.

ii) Ground motion may be amplified if:

- frequency matches the wave resonance of the structure that the energy wave is passing through i.e. sedimentary basin or building.
- exposed or subsurface materials (natural or artificial) are unconsolidated.

iii) Energy waves may be focused by:

- varying thicknesses of sedimentary layers.
- sudden change of depth of buried bedrock topography.
- a rupture reaching the surface, when effects may be locally extreme.

Subsidence and uplift can occur on a local fault scale e.g. SFZ, or the grand scale e.g. Cascadia megathrust.

Secondary causes

Earthquake-generated ground failure can cause more damage to structures than from ground shaking:

i) Landslides can directly damage people and property or create tsunamis. Shallower earthquakes cause more slides and greater losses in areas of deforestation and ground which is already saturated from heavy seasonal rainfall.

ii) Liquefaction occurs when saturated, unconsolidated deposits are shaken violently, rearranging individual grains, which causes compaction if water can escape, and quicksand if it can not.

iii) Lateral spreading fills topographical depressions (McCulloch & Bonilla, 1970) possibly compromising foundations of bridge supports and underground structures.

iv) Differential compaction can cause structural damage when foundation materials have different physical properties i.e: tidal flat sediments and building rubble.

Tsunami could also be generated by abrupt movement of large volumes of water caused by the rupture of a fault beneath Puget Sound or from delta failure. Funnelling long distances up an inlet or a river is possible, especially if on an incoming tide. The above was summarised from a section of Noson *et al.* (1988).

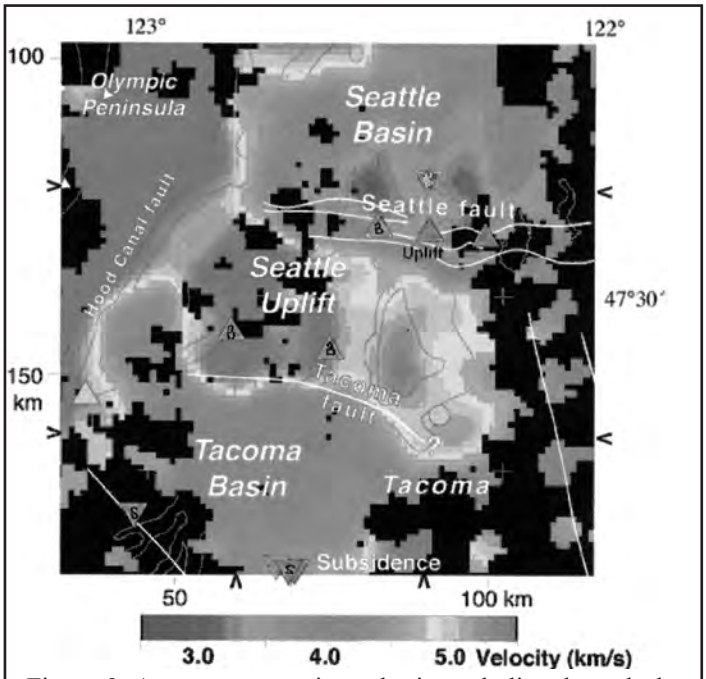


Figure 9. A map representing a horizontal slice through the earth at a depth of 3km below Puget Sound. Seismic velocities were determined by SHIPS with inferred fault zones shown. From USGS SHIPS 2001, Fig. 2.

The Tacoma fault zone is inferred from SHIPS results, as well as previous mapping of the Earth's gravity and magnetic fields (Brocher *et al*. 2001). >5.0km/s corresponds to bedrock and <5.0km/s sediment filled basins.

▲ represents uplift (Bucknam *et al.*, 1992) and ▽ subsidence (Sherrod, 2001).

Figure 11 categorises the damage which could be expected from the three types of earthquakes (Seattle Post-Intelligencer 2002). CSZ earthquakes create low frequency energy waves, which attenuate more slowly with distance from the focus and would cause moderate surface shaking, for several minutes in the Puget Sound and Lowland area. Deep earthquake waves attenuate more quickly causing moderate shaking but only for seconds. Crustal earthquake waves, being closer to the surface, would cause violent shaking for up to one minute. As a general rule, an increase in magnitude of 0.3, the difference between the 1949 Olympia M7.1 and the 2001 Nisqually M6.8, means ground motion is twice and energy three times the intensity (USGS 2003).

People are usually more vulnerable to the secondary effects of an earthquake depending upon the time of day they occur. Economic disruption is the ultimate effect of a damaging earthquake which could take many years to rectify (Pierce County 2002).

Vulnerability of the Tacoma area to Earthquake-induced damage.

Tacoma City is built upon glacial deposits and lahars from Mount Rainier. Puget Sound marine bluffs, delta and coastal water-laden areas are all vulnerable to slope failure from locally felt earthquakes. The site of a previous large landslide could also be reactivated during an earthquake as was seen at Salmon Beach during the Tacoma (1949) and Nisqually (2001) earthquakes (Figure 12) (WMD, 2003).

After the Nisqually earthquake, the Puyallup Delta was surveyed and a 2.615km^3 failure scar could be seen, where a sediment loaded landslide had caused a 3m tsunami to flow into Old Tacoma in 1894. Although the resolution of the survey was not high enough to ascertain whether 25m x 5m craters could be attributed to the Nisqually earthquake, this information can be compared against any future surveys (Gardner *et al.* 2001).

Although there is no danger from Pacific Ocean tsunamis affecting the coastal Tacoma area (Pierce County 2002) the East Passage (Figure 2) could funnel a SFZ-generated tsunami towards Tacoma especially if on a rising tide.

HAZUS, a standardised software programme, was used to test the expected damage along the main highway between Tacoma and

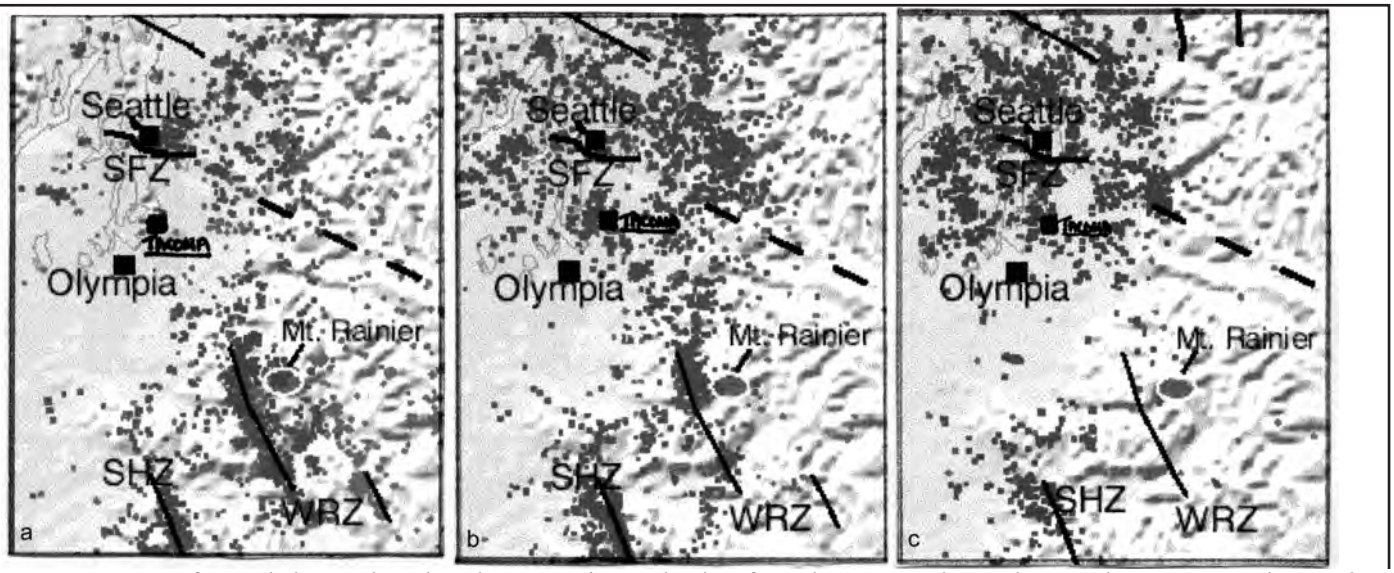


Figure 10. Images of recorded crustal earthquakes occurring at depths of 0-10km, 10 – 20km and 20 - 30km. From Stanley *et al.* 1999, Figs. 47, 48 and 49, with explanations from their text.
a) At 0 – 10km depth earthquakes are clustered along the West Rainier fault zone (WRZ) and North of the SFZ, with very few around Tacoma.
b) At 10 – 20km depth earthquakes appear to trend from the WRZ, NNW towards Tacoma.
c) At 20 – 30km depth earthquakes are more constrained within the Puget Sound area.

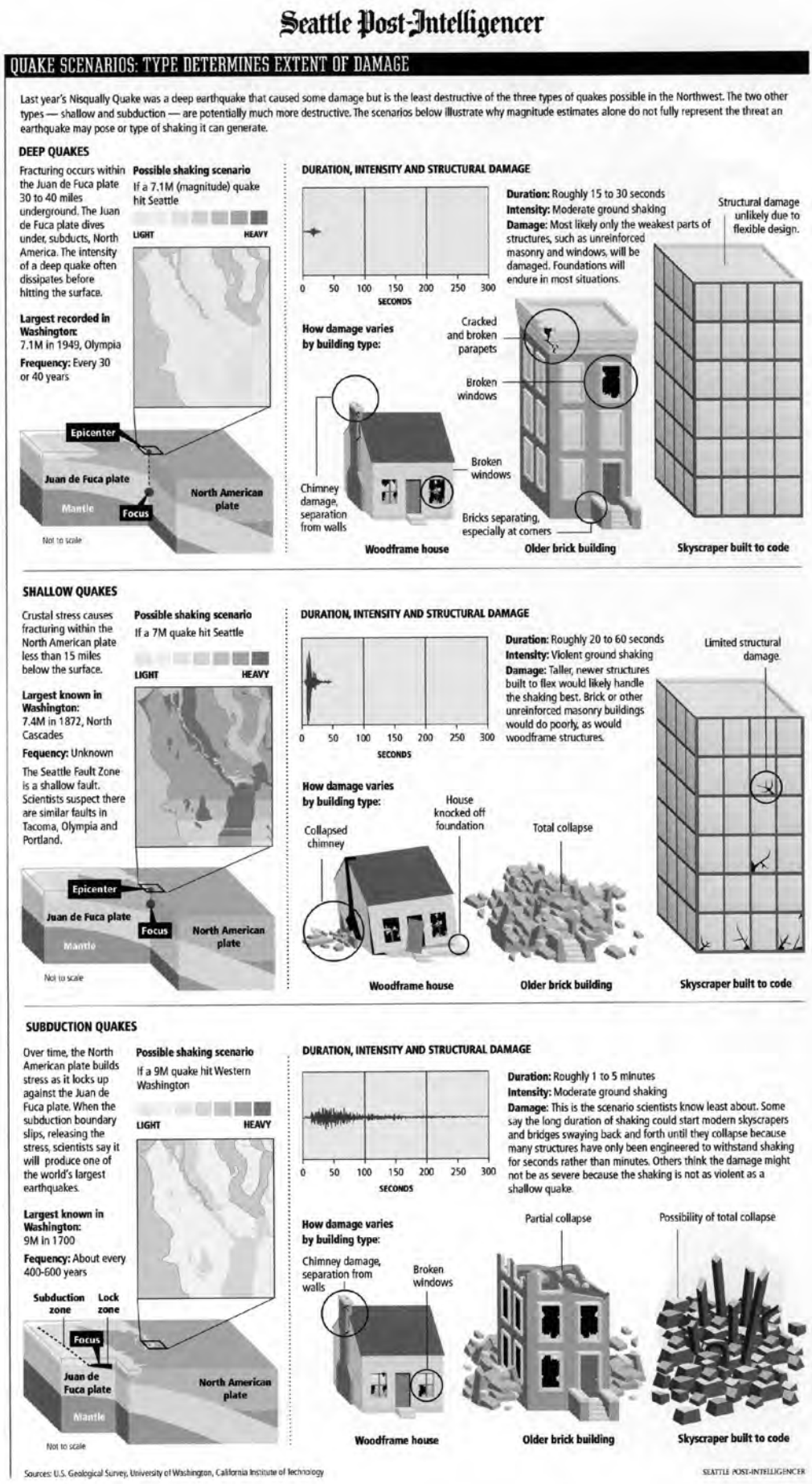

Seattle Post-Intelligencer
QUAKE SCENARIOS: TYPE DETERMINES EXTENT OF DAMAGE
Last year's Nisqually Quake was a deep earthquake that caused some damage but is the least destructive of the three types of quakes possible in the Northwest. The two other types — shallow and subduction — are potentially much more destructive. The scenarios below illustrate why magnitude estimates alone do not fully represent the threat an earthquake may pose or type of shaking it can generate.
DEEP QUAKES
Fracturing occurs within the Juan de Fuca plate 30 to 40 miles underground. The Juan de Fuca plate dives under, subducts, North America. The intensity of a deep quake often dissipates before hitting the surface.
Largest recorded in Washington: 7.1M in 1949, Olympia
Frequency: Every 30 or 40 years
Possible shaking scenario
If a 7.1M (magnitude) quake hit Seattle
LIGHT
HEAVY
Epicenter
Juan de Fuca plate
Mantle
Focus
North American plate
Not to scale
DURATION, INTENSITY AND STRUCTURAL DAMAGE
0 50 100 150 200 250 300
SECONDS
Duration: Roughly 15 to 30 seconds
Intensity: Moderate ground shaking
Damage: Most likely only the weakest parts of structures, such as unreinforced masonry and windows, will be damaged. Foundations will endure in most situations.
Structural damage unlikely due to flexible design.
How damage varies by building type:
Cracked and broken parapets
Broken windows
Broken windows
Chimney damage, separation from walls
Bricks separating, especially at corners
Woodframe house
Older brick building
Skyscraper built to code
SHALLOW QUAKES
Crustal stress causes fracturing within the North American plate less than 15 miles below the surface.
Largest known in Washington: 7.4M in 1872, North Cascades
Fequency: Unknown
The Seattle Fault Zone is a shallow fault. Scientists suspect there are similar faults in Tacoma, Olympia and Portland.
Possible shaking scenario
If a 7M quake hit Seattle
LIGHT
HEAVY
Epicenter
Juan de Fuca plate
Focus
Mantle
North American plate
Not to scale
DURATION, INTENSITY AND STRUCTURAL DAMAGE
0 50 100 150 200 250 300
SECONDS
Duration: Roughly 20 to 60 seconds
Intensity: Violent ground shaking
Damage: Taller, newer structures built to flex would likely handle the shaking best. Brick or other unreinforced masonry buildings would do poorly, as would woodframe structures.
Limited structural damage
How damage varies by building type:
Collapsed chimney
House knocked off foundation
Total collapse
Woodframe house
Older brick building
Skyscraper built to code
SUBDUCTION QUAKES
Over time, the North American plate builds stress as it locks up against the Juan de Fuca plate. When the subduction boundary slips, releasing the stress, scientists say it will produce one of the world's largest earthquakes.
Largest known in Washington: 9M in 1700
Fequency: About every 400-600 years
Possible shaking scenario
If a 9M quake hit Western Washington
LIGHT
HEAVY
Subduction zone
Lock zone
Focus
Juan de Fuca plate
Mantle
North American plate
Not to scale
DURATION, INTENSITY AND STRUCTURAL DAMAGE
0 50 100 150 200 250 300
SECONDS
Duration: Roughly 1 to 5 minutes
Intensity: Moderate ground shaking
Damage: This is the scenario scientists know least about. Some say the long duration of shaking could start modern skyscrapers and bridges swaying back and forth until they collapse because many structures have only been engineered to withstand shaking for seconds rather than minutes. Others think the damage might not be as severe because the shaking is not as violent as a shallow quake.
How damage varies by building type:
Partial collapse
Possibility of total collapse
Chimney damage, separation from walls
Broken windows
Woodframe house
Older brick building
Skyscraper built to code
Sources: U.S. Geological Survey, University of Washington, California Institute of Technology
SEATTLE POST-INTELLIGENCER

Figure 11. Damage caused by subduction, deep and crustal earthquakes as featured in the Seattle Post-Intelligencer on 27th February 2002.

Figure 12. Photographs showing landslides at Salmon Beach after the Tacoma earthquake 1949 and after the Nisqually earthquake of 2001. (WMD 2003)

Seattle for CSZ, SFZ and TFZ earthquake scenarios. Two million people live and work along this N-S corridor. The Puyallup River, bounded by liquefiable soils, proved to be a major geographic barrier, with >90% probability of roads closed for both a M6.5 Tacoma and M9 Subduction earthquakes. As a consequence of this study, Pierce County is developing a detour contingency plan, but major disruption to the population and to the economy would still be caused (EQE 2001).

Earthquake mitigation

Earthquakes cannot be prevented but mitigation of their effects can be addressed. Rapidly rising costs associated with natural disasters, has meant mitigation has become a federal, State and local priority (Pierce County 2003).

In 2000, US Congress passed the Disaster Mitigation Act, which enables the Federal Emergency Management Agency (FEMA), Pre-Disaster Mitigation programme to grant funds to States, local governments and Indian Tribes, provided they submit an approved local mitigation plan to FEMA before 1st November 2004 (Pierce County, 2003). Washington State and Pierce County are in the process of formulating plans for the County and will do so for Tacoma City. These mitigation plans will not be finalised until the Lidar results are released. However, Pierce County Mitigation Planner Program Co-ordinator indicated that even so, they were "trying to get a land use measure passed to exclude building over the fault!" (Meyers 2003).

Mitigation is defined by FEMA as "sustained action that reduces or eliminates long-term risk to people and property from natural hazards and their effects". Successful mitigation requires a) quantified understanding of the hazard, b) formulation of an appropriate plan and c) effective communication to all.

Pacific Northwest faults are complex and not fully understood which makes earthquake prediction very difficult (PNSN, 2003). Organisations therefore have to rely upon ongoing research, Earthquake Hazard Maps (USGS, 2003) as shown in Figure 13, and simulation computer programmes like HAZUS, to formulate mitigation plans. Cities and counties rely on the seismic design provisions in building codes to ensure that structures can resist earthquakes. Civil engineers need to estimate the stability and landslide potential of hillsides. The Environmental Protection Agency has to ensure the safety of waste-disposal facilities, and property owners have to decide on whether it is necessary to spend money on retrofitting their properties to guard against possible earthquake damage (USGS 2003). Such proactive mitigation measures can be as simple as making sure gas boilers, computers, bookcases are secure and that heavy pictures etc. are hung away from beds or seating areas or as grand as major strengthening of older structures built prior to modern building codes (University of Puget Sound 2001).

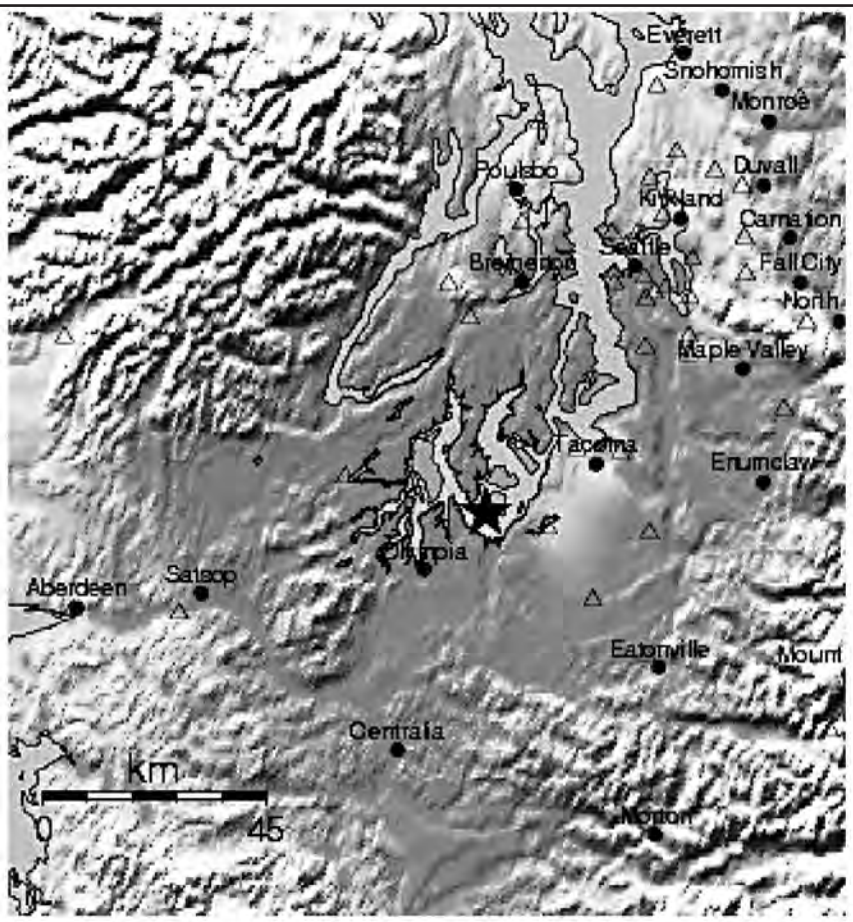
Information of mitigation measures has to be communicated to everyone whether at home, school or at places of work (WMD, 2003). On the 3 April 2003, Washington State organised a statewide earthquake drill, as part of the 2003 Disaster Preparedness Month. Notification of this event and "Drop, Cover and Hold" leaflets were distributed. A "Partners in emergency Preparedness conference" was also held to explain the new Disaster Mitigation Act 2000 and to discuss how to make Emergency Information centres work better (CAPPS, 2003). The Western States Seismic Policy Council meets annually to discuss earthquake mitigation and loss reduction. (WSSPC, 2003).

To be effective though, mitigation education has to be obvious all the time. Pierce County and Seattle City web sites have up-to-date earthquake research information and mitigation advice which is easily accessed (Pierce County 2003) (City of Seattle 2003). The Tacoma City web site has only basic earthquake preparedness information (City of Tacoma 2003). However, they are in the process of applying to Washington State for funding to produce a mitigation plan (McQuillin 2003) and hopefully a more informative web site will follow.

Discussion

Tacoma and the Cascadia subduction zone earthquake potential.

Globally, total length subduction zone ruptures are rare. Only the 1964, M9.2 Alaska and 1960, M9.5 Chile earthquakes have occurred during the last 100 years. During the 1964 Alaska earthquake, Anchorage, 120km from the epicentre, suffered substantial building damage, during the three minutes of shaking, and a zone of subsidence covered ~285 000 km^2 (USGS 2003). If the transition interface is partially locked below the Tacoma and Olympia area, stronger ground motion would be experienced, than if the focus of a CSZ earthquake was over 100km away. The paleoseismic marine turbidite record, the long inter-earthquake period and GPS studies which imply the CSZ is not segmented, means that such a M9 earthquake cannot be ruled out. Although the turbidite



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 13. Earthquake Hazard Map. Intensity map for 28 February 2001 Nisqually earthquake. From PNSN 2003 Shake Maps.

Ground shaking is perceptible to humans if the acceleration exceeds 1/10 of 1%g. Structural damage in buildings not designed to be resistant usually occurs at 10%g. Accelerations caused by earthquakes have been recorded exceeding 100%g. Factors other than acceleration must also be considered in evaluating the causes of damage such as the oscillation frequency and the total duration of shaking. For example, tall buildings are most affected by low frequency ground motions, while typical family residences are most affected by high frequency motions.(CREW, 2003).

record suggested a 600-year-average interseismic period, ~300 years was the shortest recorded. The Pacific Northwest must, therefore be prepared.

Tacoma and the Deep, within JDF Plate earthquake potential.
Deep earthquakes, like the Nisqually 2001, Olympia 1949 and Tacoma 1965, will occur on average, every 30 – 40 years and will continue to do so in Tacoma and southern Puget Sound and Lowland, for as long as the JDFP subducts at its present rate. Figure 2 shows deep earthquakes, 1, 7 and 11 which seem to follow the SE edge of the Tacoma Basin (Figure 7) and 5, 6 and 8 trend along the TFZ. The 15.8km-deep Robinson Point crustal earthquake occurred above (Figure 6) and 30 years after, the 57km-deep Tacoma earthquake. This analysis of the position of deep earthquakes as shown, does seem to favour a coupling between the subducting JDFP and the overlying crust as suggested by Stanley et. al (1999). The significance of this was discussed in the previous section.

Tacoma and the Tacoma fault zone earthquake potential
Unlike the SFZ and LFZ, the TFZ does not trend linearly (Fig. 2) but seems to be influenced by the Hood Canal in the west (Brocher et al., 2001). In the east, the inferred N-S tear zone seen trending down through Vashion Island may well merge with the TFZ. The curved TFZ may be the result of shared stress release with the SFZ as Brocher *et al.* (2001) suggest, or some other underlying structural control yet to be discovered.

To the north of the TFZ (Figure 2), as may be expected in an area of uplift, crustal earthquakes are in the majority with nine, but south of the TFZ only three, with none of significance between Tacoma and Olympia. Figure 10a, clearly shows at 0 to 10km deep, a cluster of shallow earthquakes to the north of the SFZ with almost none to the south. This could suggest two scenarios. Firstly, the TFZ is deep rooted but without surface expression, unlike the SFZ (Brocher *et al.* 2001), or secondly, the SFZ releases stored stress at regular intervals, whilst the TFZ may release the cumulative stress stored, in one large earthquake.

The timing of both the Seattle uplift (Bucknam *et al*., 1992) and the Olympia subsidence (Sherrod, 2001) at ~1,000 years coinciding with a CSZ earthquake of around the same period (Goldfinger et al., 2001) not only suggests that the fault zones of Puget Sound are interconnected, but a CSZ earthquake could stress load these crustal zones, either rupturing coseismically or some years later. For Tacoma, the potential of a crustal earthquake is still being quantified but if the TFZ is shown to trend near or even under Tacoma, the city will have to take the threat seriously.

Earthquake effects upon Tacoma
This study clearly shows that the Tacoma area is geologically vulnerable to the effects of an earthquake. High rainfall causes landslides under normal circumstances. The Puyallup River Valley

and its artificially filled intertidal delta has been shown, by HAZUS simulation, to be vulnerable to the effects of strong ground shaking from a M9 subduction and M6.5 TFZ earthquakes. The closeness of the TFZ to the Tacoma Basin (which will amplify shaking), and to the city, the port and factories built upon the Puyallup Delta, has the potential for loss of life and damaged infrastructure. It also appears that although the Nisqually (M6.8) and Olympia (7.1) at depths of 52.4 and 54km respectively occurred in almost exactly the same place (Figure 2), their effect was different. The Olympia earthquake did more damage in Tacoma than the Nisqually earthquake did, primarily because of its higher magnitude. However, if Figure 13, is examined, Tacoma appears to have experienced a lower instrumental intensity of V for the Nisqually earthquake, significantly less than the surrounding intensities of VII. This could be the result of sparse instrumental monitoring but there could also be a structural reason for this especially as Seattle, 40 km further away from the epicentre, sustained more damage than Tacoma did. The next deep earthquake could destabilise the delta front, bringing nearer the threat of delta failure. If a tsunami were to hit, whether from delta failure or a SFZ rupture, Figure 3 shows that the factory at the mouth of the Puyallup River is not many metres above sea-level!

Tacoma and mitigation

Despite the impression given by Figure 3, Tacoma has "clear views of Mount Rainier and glistening waters of Puget Sound", "over 100 parks" and "provides year-round activities for outdoor enthusiasts" (City of Tacoma 2003). The city's aggressive policy of encouraging commerce, industry and tourism, has meant that the population has and is booming. This report detailed the initiatives currently under way for the area, and hopefully Tacoma City will have a mitigation plan and a publicity programme to inform inhabitants and businesses of the earthquake potential for the area before too long. However, for research to continue and mitigation plans to be made, funding has to be found.

Conclusion

This report strives to "establish types and depth at which earthquakes have been recorded, or may be generated and investigate known fault zones within Puget Lowland" and "collate data of past earthquakes". These objectives have largely been achieved. "Monitoring schemes which are in place and planned" involve GPS and seismic receiving stations. "Geohazard potential of earthquakes in the Tacoma area" has not been satisfactorily established, due to the infancy of research in the Puget Lowland area. Present knowledge suggests that a Cascadia earthquake will happen sometime in the future, as they have in the past. The precise effect upon the Tacoma area is a matter of debate but the threat is being taken seriously. Large deep earthquakes have been recorded in southern Puget Sound in 1949, 1965 and 2001, and will continue to happen in the future. Puget Sound and Lowland crustal fault zones are still under investigation. The newly recognised Tacoma fault zone is thought to be active but this has yet to be fully established. The "resulting primary and secondary hazards triggered" by an earthquake in the Tacoma area are well known. The area is vulnerable to all factors which amplify or focus earthquake energy waves. Plentiful information enabled the "action being taken by Washington State, Pierce County and particularly Tacoma City to mitigate the geohazard effects of a potential earthquake" objective to be fulfilled.

If the Lidar survey is successful in finding the on-land TFZ, research can be focused accurately to establish the fault's activity. Across mud flats, sampling can determine if and when, possible TFZ-related subsidence, uplift or tsunami has occurred in the past. A marker bed may be identified within fault scarp outcrops, allowing geological mapping of past fault movement to be made. GPS-receiving instruments could be strategically placed to specifically monitor any movement upon the fault and seismic reflection studies could map the underlying crust in more detail. Comparison of GPS data from instruments sited along the TFZ with those upon the stable craton of the NAP, could give information of possible movement and relative strain, not only N-S crustal strain but E-W subduction movement.

It would be interesting to analyse earthquake data from other subduction zones, to determine any relationship between a deep earthquake and subsequent overlying large crustal earthquakes with similar epicentres, as was seen for the Robinson Point and Tacoma earthquakes. Any relationship discovered may help to quantify earthquake potential. Pooling of knowledge obtained from global GPS monitoring of subduction zones may help scientists to establish a link between silent-slip, deep and subduction earthquakes and the significance of the ETS seismic signature, as a possible subduction or deep earthquake precursor.

Although this report has not been able to fully assess the potential subduction and crustal earthquakes in the Tacoma area, the city can no longer be complacent about earthquake potential. With increased knowledge of the area's geology, its paleoseismic history and the development of sophisticated seismic modelling programmes, perhaps Tacoma's earthquake potential can be more accurately determined. At the end of the day, successful mitigation may rest with how well Pierce County and Tacoma formulate their plan and how importantly the funding organisations view Tacoma's earthquake potential. The result of the, Lidar Survey, of the on-land section of the Tacoma Fault Zone will undoubtedly be a pivotal point for future scientific and mitigation action.

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Addendum

Coincidentally "Mother Earth" has recently demonstrated the devasting consequences that a M9 subduction and M7.6 crustal earthquake can have. On Boxing Day 2004, a rupture occurred along at least a 500km length of the subduction interface between the Indian and Burma plates. In the mountainous region of Kashmir, Pakistan on 8th October 2005, as a direct result of India colliding with Eurasia, a 10km deep earthquake displayed what happens when the energy waves are not attenuated sufficiently with distance from the focus[1]. Results of the airborne laser mapping of the Tacoma fault zone and subsequent excavations on the western section have revealed that the fault is active and confirmed that it projected into the Puyallup River, Tacoma[2].

[1]http://neic.usgu.gov/neis/eq_deport/ (accessed 12th October 2005)

[2]Sherrod B L, Brocher T M, Weaver C S, Bucknam R C, Blakely R J, Kelsey H M, Nelson A R, & Haugerud R, 2004, Holocene fault scarps near Tacoma, Washington, USA. Geology(GSA) v.32 p.9-12.

Author

In the 1960's Josephine trained as a professional secretary and has worked for a variety of employers including the Research Director of the Cayman Turtle Farm. During the past three decades she has supported her husband in his career having lived in Jersey, Isle of Man, Cayman Islands (twice), Zurich, Geneva as well as in England. Always having been interested in "rocks", she began study with the OU and 2004 saw graduation with a First Class BSc(Hons) Natural Sciences with Earth Sciences Degree.

Book reviews

Sedimentary Rocks in the Field: A Colour Guide by Dorrik A V Stow, 2005, Manson Publishing, 320 pages, £19.95 (paperback) £39.95 (hardback) ISBN 1874545693 (paperback), 1874545683 (hardback)

The opening chapter gives an Overview, explaining the intention of the book as a guide, giving a brief classification of sedimentary rocks and a mention of the economic uses of sedimentary materials.

Chapter 2 deals with Field Techniques and includes safety, equipment, measurements and data records, sketches and logs, photography, etc. Sample field sketches and graphic logs illustrate how a field notebook should look. I liked the Useful Tip : "Make yourself comfortable to work – eg sit on a rock or ledge to sketch sections; retire to a bar or café when it rains".

Principal Characteristics of Sedimentary Rocks are comprehensively covered in Chapter 3 with diagrams of types of bedding and lamination, erosional features, depositional structures, post-depositional deformation, biogenic and chemogenic structures, texture and fabric and much more. There is a double page spread of hand lens photographs of sedimentary grains and a very useful table – "Common properties of sedimentary components under a hand lens for field identification of sediments and sedimentary rocks".

There then follow eleven chapters defining the main types of sedimentary rocks: there is a chapter on each of the main rock types and includes definition and range, principal characteristics, classification and occurrence. The field photographs accompanying each rock type are superb and each one has a comprehensive description.

The final chapter deals with Interpretation and Depositional Environments.

The coloured edging to the pages makes for rapid reference to different chapters. There are pages of References and Key Texts, Metric-Imperial Conversions, Index and six Appendices: Stratigraphic Timescale takes up three pages and lists all the Epochs, Mapping Symbols, Grain-size comparator chart, Sediment description checklist, Wulff stereonet for the re-orientation of paleocurrent data, and Lambert Equal-Area Projection for plotting rose diagrams of directional data. Examples of these last two are given in the text under Paleocurrent and paleoslope analysis. The grain-size comparator chart and sediment description checklist are very helpfully reproduced as flaps to the front and back covers of the book. Also on the back cover is a useful scale in centimetres for use in photographs.

This is ". . . a book to take into the field and use!" It is A5 size, 2 cms thick, very good quality shiny paper and the paperback version weighs 600g. It is rather large for most jacket pockets but recommended for inclusion in the backpack.

The book contains 50 line drawings and 425 superb colour photographs, most of which are from the author's own collection. At the fairly modest price of £19.95 for the paperback this is definitely a book to have and use.

Elizabeth Maddocks BA (Open)

Glaciers 2nd edition by Michael Hambrey and Jurg Alean, 2004, Cambridge University Press 376pp £35.00 (hardback) ISBN 0521828082.

Well, what can be said about this book? Superb! Beautiful? Magical? This book really is a stunting informative read. It comprises some three hundred and seventy six pages divided into sixteen chapters, a useful glossary of the terms used within the volume and an index. The one feature lifts this book from the run of the mill science book is the presence of three hundred plus full colour photographs to which words cannot truly do justice, but more of these later.

The layout of the chapters leads the reader step by step through the basic of glaciers, from their formation, to the different types of glaciers, the mechanics of how they wax and wane with the changes of seasons and climate, the manner in which they move. The middle group of chapters in the book look in detail at the interplay of glaciers with the environment by looking at the glacier covered continent of Antarctica, how glaciers interact with volcanoes such as often seen on Iceland and the aftermath of such events, how they shape the landscape giving rise to areas of outstanding natural beauty like the Lake District or the Swiss Alpine region and their role as a habitat of extremes for some of the worlds most adapted flora and fauna. The third section of the book peers into the role of glaciers as bringers of benefits in the guises of a secure supply of water for irrigation and energy, a source of economic benefit through tourism and destruction through flooding, mudslides, erasure of pasture farmland and settlements.The final section looks at the geological record to peer into past of glaciers and ponders their uncertain future in a seemingly warmer world.

The narrative of the book is concise and easy to follow; useful diagrams that are clear and illustrate points in the text unambiguously are provided as needed making for a coherent read but the feature of this book is surely the photography it contains. Some of the photographs are feast for the eyes and inspire awe in the natural world and its processes, from pictures of glaciers taken by satellite to simple ones provided by the authors as they carried out their research of their subject, they are used to support the text in a way that has you turning the page to see what awaits to slake the readers thirst for more imagery. This is one book that would grace any bookcase and give enjoyment to the reader.

Chris Gleeson BSc Hons (Open)